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U.S. PROVISIONAL APPLICATION TRANSMITTAL

Enclosed herewith please find the following:

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For

Sensor Device and Method of Detecting a Sensor Event

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A sensor device and a method of detecting a sensor event

Background of the Invention

Field of the Invention

The present invention relates to a sensor device and to a method of detecting a sensor event.

Description of the Related Art

AD

Magnetic transducer technology finds application in the measurement of torque and position. It has been especially developed for the non-contacting measurement of torque in a shaft or any other part being subject to torque or linear motion. A rotating or reciprocating element or an element which is subject to an axial load or to shear forces can be provided with a magnetized region, i.e. a magnetic encoded region, and when the shaft is rotated or reciprocated, such a magnetic encoded region generates a characteristic signal in a magnetic field detector (like a magnetic coil) enabling to determine torque, force or position of the shaft.

For such kind of sensors which are disclosed, for instance, in WO 02/063262, it is important to have an accurately defined magnetically encoded region which can be manufactured and calibrated with low cost.

During the lifetime of a sensor, a sensor signal may undergo undesired changes due to influences like little changes of the assembly of components of the sensor, or environmental influences like temperature changes or changes of sensor material.

Summary of the Invention

It is an object of the present invention to enable an accurate operation of a sensor even in case of changes of frame conditions under which the sensor is operated.

This object is achieved by providing a sensor device and a method of detecting a sensor event according to independent aspects of the invention mentioned in the following.

In the following, different aspects of the invention will be described.

Aspects 1 and 25 are independent aspects of the invention which may be realized with or without any other means. Aspects 2 to 24 relate to preferred embodiments of aspect 1.

1. aspect: A sensor device, comprising
an object having at least one magnetically encoded region thereon;
at least two magnetic field detectors adapted to detect, as detecting signals, a magnetic field generated by the at least one magnetically encoded region in case of a sensor event;
a processing unit coupled with the at least two magnetic field detectors to be provided with the detecting signals adapted to simultaneously process the detection signals to compensate artificial differences between the detection signals.

2. aspect: The sensor device according to aspect 1,
wherein the at least one magnetically encoded region is a permanent magnetic region.

3. aspect: The sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a longitudinally magnetized region of the object.

4. aspect: The sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a circumferentially magnetized region of the object.

5. aspect: The sensor device according to any of aspects 1, 2 or 4,
wherein the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction.

6. aspect: The sensor device according to aspect 5,

wherein, in a cross-sectional view of the reciprocating object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

7. aspect: The sensor device according to aspect 1 or 2,
wherein the at least one magnetically encoded region is a magnetic element attached to the surface of the object.

8. aspect: The sensor device according to any of aspects 1 to 7,
wherein at least one of the at least two magnetic field detectors comprises at least one of the group consisting of
a coil having a coil axis oriented essentially parallel to the object;
a coil having a coil axis oriented essentially perpendicular to the object;
a Hall-effect probe;
a Giant Magnetic Resonance magnetic field sensor; and
a Magnetic Resonance magnetic field sensor.

9. aspect: The sensor device according to any of aspects 1 to 8,
being adapted as one of the group consisting of a torque sensor for detecting a torque applied to the object, a position sensor for detecting a position of the object, an axial load sensor for detecting an axial load applied to the object and a shear force sensor for detecting a shear force applied to the object.

10. aspect: The sensor device according to any of aspects 1 to 9,
wherein the object is one of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine.

11. aspect: The sensor device according to any of aspects 1 to 10,
wherein a cross-section of the object has one of the shapes of the group consisting of an essentially circular shape, an essentially rectangular shape, an essentially triangular shape, an essentially oval shape and the shape of a toothed wheel.

12. aspect: The sensor device according to any of aspects 1 to 11,
wherein the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object to compensate artificial differences between the detection signals resulting from a vibration or a positional shift of the object.

13. aspect: The sensor device according to aspect 12,
wherein the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object at essentially the same distance from the object.

14. aspect: The sensor device according to aspect 12 or 13,
wherein the processing unit is adapted to compensate artificial differences between the detection signals by averaging the detection signals.

15. aspect: The sensor device according to any of aspects 1 to 10,
wherein the at least two magnetic field detectors are arranged at the same side of the object to compensate artificial differences between the detection signals resulting from changed properties of the environment or of at least one component of the sensor device.

16. aspect: The sensor device according to aspect 14,
wherein the at least two magnetic field detectors are arranged at the same side of the object at different distances from the object.

17. aspect: The sensor device according to aspect 15 or 16,

wherein the processing unit is adapted to compensate artificial differences between the detection signals based on a subtraction of the detection signals from one another.

18. aspect: The sensor device according to any of aspects 15 to 17,
wherein the at least one magnetically encoded region comprises a first magnetically encoded region and a second magnetically encoded region,

wherein the first magnetically encoded region is formed by applying a first electrical signal to a first portion of the object in absence of mechanical stress applied to the object;

wherein the second magnetically encoded region is formed by applying a second electrical signal to a second portion of the object in presence of mechanical stress applied to the object.

19. aspect: The sensor device according to aspect 18,
wherein the first electrical signal and/or the second electrical signal is a pulse signal or a sequence of subsequent pulse signals.

20. aspect: The sensor device according to aspect 19,
wherein, in a time versus current diagram, the pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge.

21. aspect: The sensor device according to aspect 19 or 20,
wherein the first electrical signal and/or the second electrical signal is a current or a voltage.

22. aspect: The sensor device according to any of aspects 17 to 21,
wherein the second electrical signal is applied after having applied the first electrical signal.

23. aspect: The sensor device according to any of aspects 17 to 22,

wherein the at least one magnetically encoded region is located adjacent a first magnetic field detector, and the second magnetically encoded region is located adjacent a second magnetic field detector.

24. aspect: The sensor device according to any of aspects 17 to 23,
further comprising a manipulation unit which is coupled to the processing unit to be provided with a subtraction signal representing the subtraction of the detection signals from one another, wherein the manipulation unit is adapted to eliminate artefacts by gaining the detection signals by a factor based on the subtraction signal.

25. aspect: A method of detecting a sensor event,
the method comprising the steps of
detecting, as detecting signals, a magnetic field generated by at least one magnetically encoded region of an object in case of a sensor event by at least two magnetic field detectors;
simultaneously processing the detecting signals to compensate artificial differences between the detection signals.

In the following, the above mentioned independent aspects of the invention will be described in more detail.

One idea of the invention may be seen in the aspect to enable accurate detection by providing two or more magnetic field detectors for detecting one and the same sensor event in a redundant manner. The signals of the two magnetic field detectors are then processed in a parallel manner, and the combined analysis of these measured signals serves as a basis for an elimination of artefacts with which the detection signals may contain. By considering different measurement conditions under which these signals have been captured (e.g. different distances from a magnetically encoded region, different locations of the detectors along an extension direction of the object (preferably an elongated shaft or the like), different

magnetically encoded regions in the environment, artefacts may be eliminated or reduced. For instance, the two or more signals may be averaged, or differences between such signals may be calculated. Thus, the invention provides a signal change compensation unit to remove the negative influence of unwanted signal changes to the accuracy of the sensor.

"Artificial differences" particularly may have the meaning that the differences stem from undesired artefacts which disturb the accuracy of the measurement. The invention benefits from the different extent to that the different magnetic field coils are prone to such artefacts by simultaneously analyzing the different signals to reduce the artefacts.

For instance, undesired vibrations of a reciprocating object (the position of which shall be detected magnetically) which influence a position detection signal in a negative manner can be eliminated by arranging two magnetic field sensors symmetrically at opposing sides of the shaft. A vibration increases one signal and reduces the other one, so the averaging of both signals reduces or eliminates the influence of vibration to the detected position.

Further, ageing effects (due to irreversible demagnetization or the like) or changes in the measuring environment (for instance temperature changes or slight changes of the relative orientation of different components of an array) may occur in the case of a magnetically encoded region. To avoid a decrease of the signal intensity in this case, the difference between two detected signals located at different positions with respect to the magnetic encoding region can be used to determine an amount of signal intensity reduction due to ageing effects or the like. This difference signal can be used as a control signal to control a gain factor with which detection signals an be multiplied to compensate an artificial reduction of the intensity of a signal. In other words, an automatic gain adjustment may be performed based on the difference of two detection signals detected by two different field detecting coils. An amplifier of a signal processing electronic can be controlled on the basis of a delta between two detection signals ("automatic gain controller"). Further, if desired, in case of detecting

that a remaining signal has become too small due to ageing effects, the magnetization of the magnetically encoded region can be refreshed by a so-called PCME pulse (see description below). Such a functionality can be implemented in a torque sensor, an axial load sensor, a shear force sensor or a position sensor.

Alternatively, ageing effects can be avoided by forming a hole in the object and by fasting a permanent magnet with a very stable magnetization inside said hole. Thus, an existent object (e.g. an engine shaft) can be retrofitted in a simple manner to create a sensor device with a very small liability to ageing effects.

In the following, preferred embodiments of the sensor device according to the first independent aspect of the invention will be described. However, these embodiments also apply for the method according to the other independent aspect of the invention.

The at least one magnetically encoded region of the position sensor device may be a permanent magnetic region. The term "permanent magnetic region" refers to a magnetized material which has a remaining magnetization also in the absence of an external magnetic field. Thus, "permanent magnetic materials include ferromagnetic materials, ferrimagnetic materials, or the like. The material of such a magnetic region may be a 3d-ferromagnetic material like iron, nickel or cobalt, or may be a rare earth material (4f-magnetism).

The at least one magnetically encoded region may be a longitudinally magnetized region of the (for instance rotating or reciprocating) object. Thus, the magnetizing direction of the magnetically encoded region may be oriented along the extension direction of an elongated object. A method of manufacturing such a longitudinally magnetized region is disclosed, in a different context, in WO 02/063262 A1, and uses a separate magnetizing coil.

Alternatively, the at least one magnetically encoded region may be a circumferentially magnetized region of the object. Such a circumferentially magnetized region may particularly be adapted such that the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction. This embodiment can be applied to torque sensors or to position sensors. However, in case of a position sensor, the orientation can be parallel or also antiparallel.

Thus, the magnetically encoded region may be realized as two hollow cylinder-like structures which are oriented concentrically, wherein the magnetizing directions of the two concentrically arranged magnetic flow regions are preferably essentially perpendicular to one another. Such a magnetic structure can be manufactured by the PCME method described below in detail, i.e. by directly applying a magnetizing electrical current to the reciprocating object made of a magnetizable material. To produce the two opposing magnetizing flow portions, current pulses can be applied to the shaft.

Referring to the described embodiment, in a cross-sectional view of the object, there may be a first (circular) magnetic flow having the first direction and a first radius and the second (circular) magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius.

Alternatively, the at least one magnetically encoded region may be a (separate) magnetic element attached to the surface of the object. Thus, an external element can be attached to the surface of the reciprocating object in order to form a magnetically encoded region. Such a magnetic element can be attached to the reciprocating object by adhering it (e.g. using glue), or may alternatively be fixed on the reciprocating shaft using the magnetic forces of the magnetic element.

The magnetically encoded region of the object is usually made of a magnetic or a magnetizable material. However, an object made of a non-magnetic material (like plastics or the like) may be used, when a synthetic (ferro-)magnetic magnet is attached to or embedded in the object.

Any of the magnetic field detectors may comprise a coil having a coil axis oriented essentially parallel to an extension direction of the object. Further, any of the magnetic field detectors may be realized by a coil having a coil axis oriented essentially perpendicular to the object. A coil being oriented with any other angle between coil axis and extension direction of the object is possible and falls under the scope of the invention. Alternatively to a coil in which the moving magnetically encoded region may induce an induction voltage by modulating the magnetic flow through the coil, a Hall-effect probe may be used as magnetic field detector making use of the Hall effect. Alternatively, a Giant Magnetic Resonance magnetic field sensor or a Magnetic Resonance magnetic field sensor may be used as a magnetic field detector. However, any other magnetic field detector (which is already known or which will be developed in the future) may be used to detect the presence or absence of one of the magnetically encoded regions in a sufficient close vicinity to the respective magnetic field detector.

The sensor device may be adapted as one of the group consisting of a torque sensor for detecting a torque applied to the object (when the object rotates), a position sensor for detecting a position of the object (when the object reciprocates), an axial load sensor for detecting an axial load applied to the object and a shear force sensor for detecting a shear force applied to the object.

The object may be one of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine. The method and apparatuses of the invention may be implemented in the frame of a mining shaft, a concrete processing

cylinder, a push-pull rod in a gearbox, or a shaft of an engine. In all of these applications, the compensation of sensor signal artefacts of such a torque, force and position sensor is highly advantageous, since it allows to manufacture a highly accurate and reliably force, position and torque sensor with low costs which does not have to calibrated any time a change occurs. Particularly, mining and drilling equipment may be provided with the systems of the invention, and may be used for monitoring a drilling direction and drilling forces. Further applications of the invention are the recognition and the analysis of engine knocking.

A cross-section of the object may have one of the shapes of the group consisting of an essentially circular shape, an essentially rectangular shape and an essentially triangular shape, an essentially oval shape and the shape of a toothed wheel.

According to one embodiment, the at least two magnetic field detectors may be arranged symmetrically at opposite sides of the object to compensate artificial differences between the detection signals resulting from a vibration or a positional shift of the object. For instance, a reciprocating shaft as the object of a position sensor may reciprocate along a first direction and may be subject to undesired vibrations or (static) positional shifts along a second direction which may be oriented perpendicular to the first direction. By placing two magnetic field detectors at two opposing sides of the reciprocating object (the connection line for instance being aligned along the second direction) allows a compensation of signal disturbing vibration influence by averaging the two detection signals detected by the two magnetic field detectors.

Referring to this embodiment, the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object at essentially the same distance from the object. This increases the amount of vibration influence being eliminated by the compensation calculation scheme.

Still referring to the described embodiment, the processing unit may be adapted to compensate artificial differences between the detection signals by averaging the detection signals, i.e. by calculating the mean value of the two signals.

According to an alternative embodiment, the at least two magnetic field detectors may be arranged at the same side of the object to compensate artificial differences between the detection signals resulting from changed properties of the environment or of at least one component of the sensor device. A changed property of the environment may be a changed temperature having an influence to the degree of magnetization of the magnetically encoded region. A changed property of at least one component of the sensor device may be a slightly changed geometrical arrangement of the magnetic field detectors with respect to the magnetically encoded region or a decrease of the magnetization amplitude of the magnetically encoded region due to a usage of the sensor for a very long time under harsh conditions.

Referring to this embodiment, the at least two magnetic field detectors may be arranged at the same side of the object at different distances from the object. The different distances yield different sensitivities of the at least two magnetic field detectors, so that resulting differences in the detection signals may be taken into account as useful information to compensate for artefacts to be eliminated.

Still referring to the described embodiment, the processing unit may be adapted to compensate artificial differences between the detection signals based on a subtraction of the detection signals from one another.

Particularly, the at least one magnetically encoded region may comprise a first magnetically encoded region and a second magnetically encoded region. The first magnetically encoded region may be formed by applying a first electrical signal to a first portion of the object in absence of mechanical stress (like torque) applied to the object. The second magnetically

encoded region may be formed by applying a second electrical signal to a second portion of the object in presence of mechanical stress (like a pre-selected amount of torque) applied to the object. By this concept, which is explained in further detail below (see Fig.8A to Fig.8D), an offset between signals measured in the vicinity of the first magnetically encoded region and signals measured in the vicinity of the first magnetically encoded region is generated.

The first electrical signal and/or the second electrical signal may be a pulse signal or a sequence of subsequent pulse signals. Such a pulse signal can particularly be a signal which is different from zero only for a defined interval of time.

Preferably, in a time versus current diagram, the pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge. With such a pulse signal, the magnetically encoded region obtained has a high quality. It is also possible that a plurality of such pulses are subsequently applied to form a magnetically encoded region.

The first electrical signal and/or the second electrical signal may be a current or a voltage.

The second electrical signal is preferably applied after having applied the first electrical signal.

The at least one magnetically encoded region my be located adjacent a first magnetic field detector, and the second magnetically encoded region may be located adjacent a second magnetic field detector.

The sensor device of the invention may further comprise a manipulation unit which is coupled to the processing unit to be provided with a subtraction signal representing the subtraction of the detection signals from one another, wherein the manipulation unit may adapted to eliminate artefacts by gaining the detection signals by a factor based on the subtraction signal.

In other words, an output of the processing unit may be provided as a steering signal to the manipulation unit. Based on a combined analysis of the detection signals, an amount of signal change due to artefacts like age-effects may be evaluated. The manipulating unit may use this information to adjust a gain factor for sensor signals. The stronger the sensor signal is influenced by the artefact, the higher will be the gain factor, to achieve a proper compensation.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or elements are denoted by like reference numbers.

Brief Description of the Drawings

The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

In the drawings:

Fig.1A shows a position sensor array according to a first embodiment of the invention.

Fig.1B shows a torque sensor array according to a second embodiment of the invention.

Fig.2A shows a shaft having a permanent magnet attached thereon, of a position or torque sensor array according to a third embodiment of the invention.

Fig.2B shows a shaft having a permanent magnet embedded therein, of a position or torque sensor array according to a forth embodiment of the invention.

Fig.2C shows a shaft having a permanent magnet embedded therein, of a position or torque sensor array, similar to the forth embodiment of the invention.

Fig.3A shows a position sensor array according to a fifth embodiment of the invention.

Fig.3B shows shafts with different cross-sectional geometry, each having a magnetically encoded region.

Fig.3C illustrates that a magnetically encoded region of a shaft may extend along a smaller or a larger portion along the shaft.

Fig.4A shows a perspective view of a position sensor array according to a sixth embodiment of the invention.

Fig.4B shows a cross-sectional view of the position sensor array according to the sixth embodiment of the invention.

Fig.5A shows perspective views of a position sensor array according to a seventh embodiment of the invention.

Fig.5B shows a cross-sectional view of the position sensor array according to the seventh embodiment of the invention.

Fig.6A shows a position sensor array according to an eighth embodiment of the invention.

Fig.6B shows a position sensor array according to a ninth embodiment of the invention.

Fig.7 shows a diagram illustrating detection signals as detected by magnetic field detection coils of position sensor array according to a ninth embodiment of the invention, and a correction.

Fig.8A to Fig.8D show different views of a torque sensor array according to a tenth embodiment of the invention.

Fig.9A and Fig.9B illustrate the gain of a detection signal in dependence of a distance of a magnetic field detector from a magnetically encoded region.

Fig.10A shows a torque sensor array according to an eleventh embodiment of the invention.

Fig.10B shows a torque sensor array according to a twelfth embodiment of the invention.

Fig.10C shown an exemplary set of parameters according to a APS system specification.

Fig.11 illustrates signal scans of a sensor device according to the invention.

Fig.12 to Fig.67 illustrate the PCME technology which, according to the invention, is preferably used to form at least one magnetically encoding region on at least part of a reciprocating shaft.

Detailed Description of Preferred Embodiments of the Invention

In the following, referring to Fig.1A, a position sensor array 100 according to a first embodiment of the invention will be described.

The position sensor device 100 comprises a reciprocating shaft 101 having a magnetically encoded region 102. Further, two magnetic field detecting coils 103, 104 are provided which are adapted to detect, as detecting signals, a magnetic field generated by the magnetically encoded region 102 in case of a reciprocation of the reciprocating shaft 101. A microprocessor 105 is coupled with the two magnetic field detecting coils 103, 104 to be provided with the detecting signals. The microprocessor 105 is adapted to simultaneously process the detection signals to compensate artificial differences between the detection signals.

The two magnetic field detecting coils 103, 104 are arranged symmetrically at opposite sides of the reciprocating shaft 101 to compensate artificial differences between the detection signals resulting from vibrations of the reciprocating shaft 101. The two magnetic field detecting coils 103, 104 are arranged symmetrically at opposite sides of the reciprocating shaft 101 at the same distance from the reciprocating shaft 101. The microprocessor 105 is adapted to compensate artificial differences between the detection signals by averaging the detection signals.

In the following, referring to Fig.1B, a torque sensor array 120 according to a second embodiment of the invention will be described.

In the case of the torque sensor device 120, the two magnetic field detecting coils 103, 104 are arranged at the same side of the rotating shaft 101 to compensate artificial differences between the detection signals resulting from changed properties of the environment or of at least one component of the sensor device 120. The microprocessor 105 is adapted to compensate artificial differences between the detection signals based on a subtraction of the detection signals from one another.

In the following, referring to Fig.2A, a shaft 101 having a permanent magnet 200 attached thereon, of a position or torque sensor array according to a third embodiment of the invention will be described.

Ageing effects (resulting from a loss of magnetization of a magnetically encoded region of a steel shaft which may occur during a long lifetime) can be avoided by fasting the permanent magnet 200 with a very stable magnetization as to be attached to the shaft 101 and covered with a protection element 202. Thus, the resulting sensor device has a very small liability to ageing effects.

Fig.2B and Fig.2C show, as an alternative configuration to Fig.2A, a shaft 101 having a permanent magnet 200 embedded in a hole 201 formed in the shaft 101, of a position or torque sensor array according to a forth embodiment of the invention.

Thus, a synthetic magnet 200 is used to generate a very strong magnetic field. The synthetic magnet 200 can be placed inside the beam/shaft 101 or can be mounted outside the beam/shaft 101.

In the following, referring to Fig.3A, a position sensor array 300 according to a fifth embodiment of the invention will be described.

The axial position sensor 300 comprises three modules: the magnetically encoded sensor host SH 101, the magnetic field sensor devices 103, 104, and a signal conditioning and signal processing electronics 301.

Fig.3B shows shafts 101 with different cross-sectional geometry, each having a magnetically encoded region 102.

Fig.3B shows cross-sections of the shafts 101 having an essentially circular shape, an essentially rectangular shape and an essentially triangular shape. Particularly, the PCME technology can be applied to shafts with a cross-section shape: round, square, rectangular, or any other shape. When using a round shaft, the shaft can rotate at any speed without interfering the position sensor signal quality.

Fig.3C illustrates that a magnetically encoded region 102 of a shaft 101 may extend along a smaller or a larger portion along the shaft 101. The magnetically encoded region of a shaft may also extend along the entire length of the shaft (not shown). The possible axial sensing range is a function of the shaft cross-section. For example, for a shaft cross section of 40 mm2, the full scale axial sensing length may range from 10 mm to 50 mm.

Fig.4A shows a perspective view and Fig.4B shows a cross-sectional view of a position sensor array 400 according to a sixth embodiment of the invention.

The magnetic field sensor devices 103, 104 can be placed on the side or on top of the magnetically processed shaft 101. An optimal spacing b between the two magnetic field sensor devices 103, 104 is a function of the (useful) axial sensing length and the distance c between the shaft 101 and the magnetic field sensor devices 103, 104.

Fig.5A shows perspective views of a position sensor array 500 according to a seventh embodiment of the invention. Fig.5B shows a cross-sectional view of the position sensor array 500.

The position sensor array 500 allows a real-time compensation of tolerances. In addition to the magnetic field detecting coils 103, 104, additional magnetic field detecting coils 501, 502 are provided and arranged symmetrically at two opposing sides of the shaft 101. All magnetic

field detecting coils 103, 104, 501, 502 are arranged within a casing 503, in which additionally a signal conditioning and signal processing electronics module 301 is located.

Undesired vibrations 504 of the reciprocating shaft 101 (reciprocating in a direction perpendicular to the paper plane of Fig.5B) which influence a position detection signal in a negative manner can be eliminated by arranging the magnetic field detecting coils 103, 104, 501, 502 symmetrically at opposing sides of the shaft 101. A vibration increases one signal and reduces the other one, so the averaging of both signals reduces or eliminates the influence of vibration to the detected position.

In the following, referring to Fig.6A, a position sensor array 600 according to an eighth embodiment of the invention will be described.

In the case of the position sensor array 600, the four magnetic field detecting coils 103, 104, 501, 502 are arranged at the same side of the shaft 101 to compensate artificial differences between the detection signals resulting from changed properties of the environment or of at least one component of the sensor device 600. The configuration of Fig.6A allows an automatic slope detection and slope control, wherein slope means the slope of a sensor signal (see Fig.7) which may undergo a change (particular a decrease) when properties of the environment or of the sensor device 600 change. With a dual channel APS design (coil system A&B), the system 600 can detect and respond to signal slope changes.

This allows a simplification of the sensor calibration, can compensate for assembly tolerances, and can compensate for slope changes caused by temperature, spacing, etc.

In the following, referring to Fig.6B, a position sensor array 650 according to a ninth embodiment of the invention will be described.

The position sensor array 650 is an integrated system in which the coils 103, 104, 501, 502 are integrated within a casing 503 and are connected to a signal conditioning and signal processing electronics module 301. The signal conditioning and signal processing electronics module 301 generates, as an output signal, a gain factor with which sensor signals may be multiplied to compensate signal changes due to changes in the environment and in the device 650 (e.g. temperature, assembly tolerances, material variations, system damages, etc.).

Fig.7 shows a diagram 700 illustrating, along an ordinate 702, detection signals as detected by magnetic field detection coils 103, 104, 501, 502 of the position sensor array 650, and along an abscissa 701 and axial movement of the shaft 101.

When ageing effects or the like occur, the slope of the curves in Fig.7 decrease, and so does the difference signal A-B, so that the change of the difference signal A-B can be used to manipulate a sensor signal in such a manner to compensate such changes.

In the following, referring to Fig.8A to Fig.8D, a torque sensor array 800 according to a tenth embodiment of the invention will be described.

The Non-Contact PCME sensing technology requires that, preferably, the Secondary Sensor is placed at a fixed distance in relation to the Primary Sensor. To give a further explanation, the "radial" spacing between the Secondary Sensor module and the Sensor Host surface (or shaft surface) should be kept constant.

The signal strength, emitted from the Primary Sensor, will degrade rapidly the further away the receiving Secondary Sensor module is placed. In case of an application where the entire sensor system is exposed to strong vibrations (example: Combustion engine, or impact power tools), it is possible that the PCME sensor output signal will show the effect of the system

vibration in form of a signal amplitude modulation. The same could happen in an application where changes in the ambient temperature has an effect on the mechanical position of the Secondary Sensor module in relation to the Primary Sensor location (example: different temperature expansions of materials used for the physical sensor design.

This issue can be controlled and dealt with by applying the proper care when designing the sensor system (using strong bearings, assuring that the temperature coefficient is matching for the different mechanical sensor modules / components). However, the circumstances may make it impossible to assure that the mechanical precision and stability required can be guarantied and therefore the "radial" spacing may vary during the use of the sensor system.

The described invention provides a fully automatic compensation for the otherwise unwanted effects when the "radial" spacing is changing between the Secondary Sensor module and the Primary Sensor. This aspect of the invention is called here "Automatic Slope Control", or ASC.

This aspect of the invention is also capable to deal with the unwanted effects of sensor signal ageing in case the sensor system has been exposed to mechanical overload. To give a further explanation, in case the Sensor Host will be stressed to and beyond the point where "plastic" deformation of the Sensor Host is taking place, the PCME signal begins to weaken permanently (this phenomena is typical for many sensing technologies that rely on the principles of magnetostriction). This is here called "Sensor Ageing".

The ASC technology is capable to compensate for the effects of sensor ageing.

To achieve the ASC effect, a magnetic reference signal may be placed inside the Sensor Host. The Sensor Host will then carry the magnetic encoding of the PCME technology and a magnetic reference encoding in parallel to each other. It is the objective that the magnetic

PCME encoding will continue to respond to the physical stresses applied to the Sensor Host, while the magnetic reference encoding will only react to the effects of sensor ageing.

This ASC reference signal is placed in the SH during the PCME encoding process. Normally the PCME process is applied to the Sensor Host (SH) while the SH (or shaft) is in relaxed state (no mechanical stresses are applied to the SH). In case of the ASC technology, two PCME encoding processes will take place in succession (not in parallel) while one PCME process takes place in "relaxed" state, the other PCME process takes place while a known mechanical force (like torque) is applied to the SH.

By applying mechanical stress (like a torque force) to the SH during the PCME encoding process, the output signal of the final sensor system will have an electrical offset that is proportional to the applied mechanical stress.

Referring to Fig.8A and Fig.8B, a Dual PCME Field encoding is required to achieve the ASC effect. While one PCME encoding process happen while NO mechanical forces are applied to the shaft 101, the other PCME encoding takes place while a known mechanical force (like torque) is applied to the 101. In principle there are no obligations in which order these process steps take place.

According to the described embodiment of the ASC technology, the magnetically encoded region of the sensor device 800 comprises a first magnetically encoded region 801 and a second magnetically encoded region 802. The first magnetically encoded region 801 is formed by applying a first electrical signal to a first portion of the shaft 101 in absence of mechanical stress applied to the shaft 101. The second magnetically encoded region 802 is formed by applying a second electrical signal to a second portion of the shaft 101 in presence of mechanical stress applied to the shaft 101.

The first electrical signal and the second electrical signal are each pulse signals. In a time versus current diagram, the pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge (see Fig. 30). The second electrical signal is applied preferably after having applied the first electrical signal.

Referring to Fig.8C and Fig.8D, to recover the ASC reference signal, at least two MFS devices 103, 104 are needed that will form the Secondary Sensor Unit. It is preferred that the two MFS devices 103, 104 needed are mounted on the same frame to ensure that any change of spacing between the Secondary Sensor Unit and the Sensor Host (SH) 101 will effect both MFS devices 103, 104 in exactly the same way.

It is also preferred that a SCSP (Signal Conditioning & Signal Processing) electronics 301 for both channels (MFS1 103 and MFS2 104) are effected by the changes of supply voltages and ambient temperature changes in exactly the same quantitative way. Otherwise the ASC reference signal will not be reliable enough to achieve the desired performances.

As can be seen from Fig. 8C, when the SH (Sensor Host or shaft) 101 is in the relaxed state, the output signals from the two, independent working Secondary Sensor & SCSP (Signal Conditioning & Signal Processing) Channels (Output 1 and Output 2) reading the values: +2,500V and 2.000V. The difference between these two voltages is dependent on the applied mechanical force during the PCME SH processing, the gain setting of the SCSP electronics, and the spacing between the MFS and the SH-Shaft surface. In this example the difference is 2.500 V – 2.000 V = 0.500 V. This 0.500 V represent the ASC reference signal. Under normal condition the ASC reference signal remains constant.

As can be seen from Fig. 8D, when applying a specific torque force to the SH 101, the output voltages from both SCSP channels will change by the same amount. The change in output voltage is a proportional function of the applied mechanical force. However, the difference in

the output Voltage from Channel 1 and Channel 2 remains constant (in this example: 3.200 V – 2.700 V = 0.500 V).

The signal increase from channel 1 (as a consequence of the applied torque force) is the difference between the two measurements: 3.200 V – 2.500 V = 0.700 V. The signal slope is a function of the spacing between the Primary Sensor (surface of the SH) 101 to the Secondary Sensor (MFS device) 103, 104.

Referring to Fig.9A, as the spacing between the MFS (also called Secondary Sensor) 103, 104 is increasing (like from the values S1 to the value S2), the signal amplitude will drop.

Referring to Fig.9B, with increasing spacing between the Secondary Sensor (MFS device) 103, 104 and the Primary Sensor (SH surface) 101, the absolute signal amplitude will drop rapidly (function of the power to the spacing).

In the same way the signal amplitude will drop, so will the ASC signal. The ASC signal is the difference between the output voltages from Channel 1 and Channel 2.

Fig.10A shows a block diagram 1000 of the ASC electronics. In this simplified example, the sensor signal, generated by the Secondary Sensor device MFS 1 103, will be amplitude modulated in a Programmable Gain Stage 1001. The difference between the signals of MFS1 103 and MFS2 104 is processed in a comparator 1002. The output signal of the module "Comparator" 1002 is the "Gain Control Signal" of the Programmable Gain Stage 1001. The larger the signal difference between MFS1 103 and MFS2 104, the lower the gain setting of the Programmable Gain Stage 1001 has to be. The lower the signal difference between MFS1 103 and MFS2 104, the higher the gain setting of the Programmable Gain Stage 1001 has to be.

With the increase of the gain setting, the Signal-to-Noise ratio will become poorer. Meaning that at some point the signal generated by MFS1 103 is so small that a high gain setting will amplify mainly the noise and consequently the resulting "Corrected Output Signal" is no longer of any use.

In this description "in-line" or "axial" positioned MFS devices have been used. However, this technology will work the same when using radial or tangentially placed MFS devises. Which way the MFS device has to be placed depends on what mechanical forces need to be measured and what type of mechanical force has been applied to the SH during one of the PCME encoding process.

The ASC technology is a true Non-Contact solution to detect and to correct changes of the PCME output signal amplitude caused by mechanical failures of the sensor system.

The ASC technology detects and corrects the changes of the output signal amplitude, caused by sensor ageing or by changes in the spacing between the Primary and Secondary Sensor. The space changing may be caused through mechanical damages in the sensor assembly, the effects of temperature (differences in physical expansion of the sensor material), or through mechanical vibrations in the sensor system.

The ASC technology will eliminate the need for sensors "gain"-setting calibration as the ASC reference signal gives a true representation of the sensor systems response to applied mechanical forces.

This technical solution does not require any more spacing on the SH. Meaning that the mechanical dimensions and the physical design of the "dual field" PCME sensor remains the same. There is no need to attaché any device or any substance on the SH and therefore the outstanding performances of the PCME sensor are not affected by the ASC technology.

The required electronics of the ASC solution is of low complexity and can be realized in analog signal processing technology or by using mixed signal (analog and digital) technology. When using the mixed signal approach there will be no need for any additional electronic component to implement the ASC technology. Meaning: no cost increase.

The ASC technology can correct in real-time the output signal of a PCME sensor system. The output signal correction includes:

- Fully compensating the effects of unwanted changes in the spacing of the Secondary Sensor module during measurements
- Compensating the effects of sensor ageing, caused by applying a mechanical overload to the Primary Sensor device.
- Fully compensating the effects of gain changes in the SCSP electronics stages caused by the influence of ambient temperature changes.
- Eliminates the need for the sensors gain / slope calibration. The ASC reference signal can be used to define the actual sensor response to mechanical forces applied to the SH (or Primary Sensor).

The ASC technology may not add any costs in the actual sensor system and can be applied during the actual PCME encoding procedure.

The ASC technology is applicable to all PCME sensor designs where mechanical forces (like torque, axial forces, bending) or a position (rotational and linear) needs to be measured accurately. Particularly important is this technology for applications where there is a risk of mistreating the sensor system (detecting and compensating for the effects of applying a mechanical overload (resulting in Sensor Ageing): Motor Sport, Industrial Drilling Applications, Impact and Impulse Power Tools.

Fig.10B shows a block diagram 1050 of the ASC electronics according to another embodiment.

This sophisticated electronic includes a dual channel processing (slope control), temperature compensation, signal mapping (if needed or desired), and a protocol generator.

Fig.10C shown an exemplary set of parameters according to a APS system specification.

The next drawing shows the sensor system output signal as a function of the axial (in-line) location at the Primary Sensor region.

Fig.11A shows the Sensor system output signal when moving one MFS device along the PCME encoded sections (Primary Sensor region). This graph has been generated from a Dual Field PCME sensor with reversed polarity encoding (process described in Fig.8A, Fig.8B).

The reversed polarity encoding makes it simpler to cancel the effects of parallel / uniform magnetic stray fields, like the Earth Magnetic Field (EMF). This can be achieved by subtracting the output signals MFS1 from MFS2.

However, the ASC technology also works on a Dual Field PCME sensor with not reversed polarity encoding (see below).

Fig.11B shows the Sensor System output signal when moving one MFS device axially along the Primary Sensor region. This graph comes from a Dual Field, not reversed polarity PCME sensor with ASC technology. The step function in the signal lines is caused by the PCME encoding while the sensor has been under mechanical stress (like torque).

It has been described an ASC encoding process whereby only one PCME encoding step has been performed with physical load applied to the SH. It is possible to achieve a much larger signal step function when both PCME encoding steps are performed while a mechanical load is applied to the SH. However the mechanical load applied to the SH has to be in opposite direction to assure that the desired ASC reference signal can be generated.

In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to a preferred embodiment of the invention, be implemented to form a magnetically encoded region and to detect a position information of a reciprocating object. In the following, the PCME technology will partly described in the context of torque sensing. However, according to the invention, this concept is implemented in the context of the position sensing of the invention.

In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many terms that are particularly related to the magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology or to PCME, it is referred to exemplary embodiments of the present invention.

Table 1 shows a list of abbreviations used in the following description of the PCME technology.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria

Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

Table 1: List of abbreviations

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and

others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a “closed-loop” magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

Fig.12 shows that two magnetic fields are stored in the SH and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

Fig.13 illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in Fig.14, when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the magnetic flux lines tilt in proportion to the applied stress (like linear motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

Referring to Fig.15, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.

Referring to Fig.16, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

- No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- Very good RSU (Rotational Signal Uniformity) performances
- Excellent measurement linearity (up to 0.01% of FS)
- High measurement repeatability
- Very high signal resolution (better than 14 bit)
- Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

- More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- Easy and simple shaft loading process (high manufacturing through-putt).
- No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- Sensitive to mechanical forces in all three dimensional axis.

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and

well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are travelling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").

Referring to Fig.17, an assumed electrical current density in a conductor is illustrated.

It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.

Referring to Fig.18, a small electrical current forming magnetic field that ties current path in a conductor is shown.

It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the conductor.

Referring to Fig.19, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at

the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.

Referring to Fig.20, a uniform current density in a conductor at saturation level is shown.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

Referring to Fig.21, electric current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).

Referring to Fig.22, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).

Again referring to Fig.13, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to Fig.23, magnetic field structures stored near the shaft surface and stored near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.

Referring to Fig.24, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is cancelling out the measurable effects in the inner halve of the "U".

Referring to Fig.25, the zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have cancelled-out each other (G).

Referring to Fig.26, the zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic

field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

In the following, a Rectangle Current Pulse Shape will be described.

Referring to Fig.27, a rectangle shaped electrical current pulse is illustrated.

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.

Referring to Fig.28, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

Referring to Fig.29, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

In the following, a Discharge Current Pulse Shape is described.

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in Fig.30, a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

Referring to Fig.31, a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

Referring to Fig.32, Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will

begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

Referring to Fig.33, Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

Referring to Fig.34, better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

Referring to Fig.35, flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor Processing will be described.

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I).

Referring to Fig.36, a simple electrical multi-point connection to the shaft surface is illustrated.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to Fig.37, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.

Referring to Fig.38, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to Fig.39, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

Referring to Fig.40, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

Referring to Fig.41, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

Referring to Fig.42, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC. Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

Referring to Fig.43, the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.

Fig.44 shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

Referring to Fig.45, magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to Fig.46, when torque forces or linear stress forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to Fig.47, when the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.
In the following, a Multi Channel Current Driver for Shaft Processing will be described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.

Referring to Fig.48, a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

In the following, Bras Ring Contacts and Symmetrical "Spot" Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

Referring to Fig.49, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.

Referring to Fig.50, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to Fig.51, a PCME processed Sensing region with two "Pinning Field Regions" is shown, one on each side of the Sensing Region.

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.

Referring to Fig.52, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

Referring to Fig.53, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

Referring to Fig.54, when the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

Referring to Fig.55, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in Fig.57, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

Fig.58 shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".

In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- ICs (surface mount packaged, Application-Specific Electronic Circuits)
- MFS-Coils (as part of the Secondary Sensor)
- Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

Fig.59 shows components of a sensing device.

As can be seen from Fig.60, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.

In the following, a control and/or evaluation circuitry will be explained.

The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

- Basic Circuit
- Basic Circuit with integrated Voltage Regulator
- High Signal Bandwidth Circuit
- Optional High Voltage and Short Circuit Protection Device
- Optional Fault Detection Circuit

Fig.61 shows a single channel, low cost sensor electronics solution.

Fig.62 shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in Fig.63, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment- & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become

increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- custom made SSU (including the wire harness and connector)
- selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

Fig.64 illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.

Fig.65 illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.
As illustrated in Fig.66, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in Fig.67.

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ...) and so does the processing equipment required. Some of the available magnetostriction sensing technologies

do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- High production quantities (like in the thousands)
- Heavy or difficult to handle SH (e.g. high shipping costs)
- Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

It should be noted that the term "comprising" does not exclude other elements or steps and the "a" or "an" does not exclude a plurality. Also elements described in association with different embodiments may be combined.

What Is claimed is:

A sensor device, comprising
an object having at least one magnetically encoded region thereon;
at least two magnetic field detectors adapted to detect, as detecting signals, a magnetic field generated by the at least one magnetically encoded region in case of a sensor event;
a processing unit coupled with the at least two magnetic field detectors to be provided with the detecting signals adapted to simultaneously process the detection signals to compensate artificial differences between the detection signals;
wherein the at least one magnetically encoded region is a circumferentially magnetized region of the object;
wherein the at least one magnetically encoded region is formed by a first magnetic flow region oriented in a first direction and by a second magnetic flow region oriented in a second direction, wherein the first direction is opposite to the second direction;
wherein, in a cross-sectional view of the reciprocating object, there is the first circular magnetic flow having the first direction and a first radius and the second circular magnetic flow having the second direction and a second radius, wherein the first radius is larger than the second radius;
wherein each of the at least two magnetic field detectors is a coil having a coil axis oriented essentially parallel to the object;
wherein the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object to compensate artificial differences between the detection signals resulting from vibrations of the object;
wherein the at least two magnetic field detectors are arranged symmetrically at opposite sides of the object at the same distance from the object;
wherein the processing unit is adapted to compensate artificial differences between the detection signals by averaging the detection signals.

Abstract

A sensor device and a method of detecting a sensor event

A sensor device comprises an object having at least one magnetically encoded region thereon, at least two magnetic field detectors adapted to detect, as detecting signals, a magnetic field generated by the at least one magnetically encoded region in case of a sensor event, and a processing unit coupled with the at least two magnetic field detectors to be provided with the detecting signals adapted to simultaneously process the detection signals to compensate artificial differences between the detection signals.

(Fig.6A)

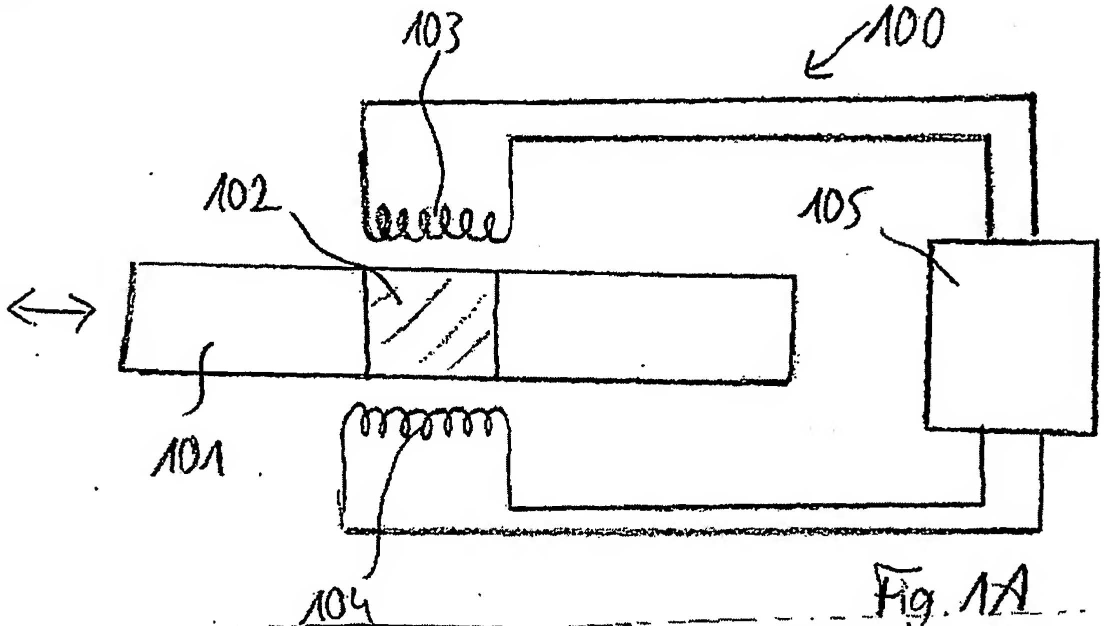


Fig. 1A

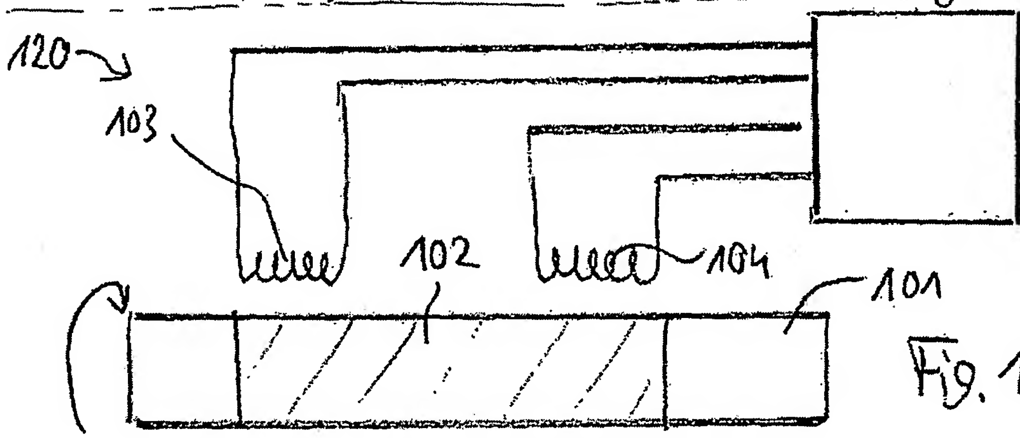


Fig. 1B

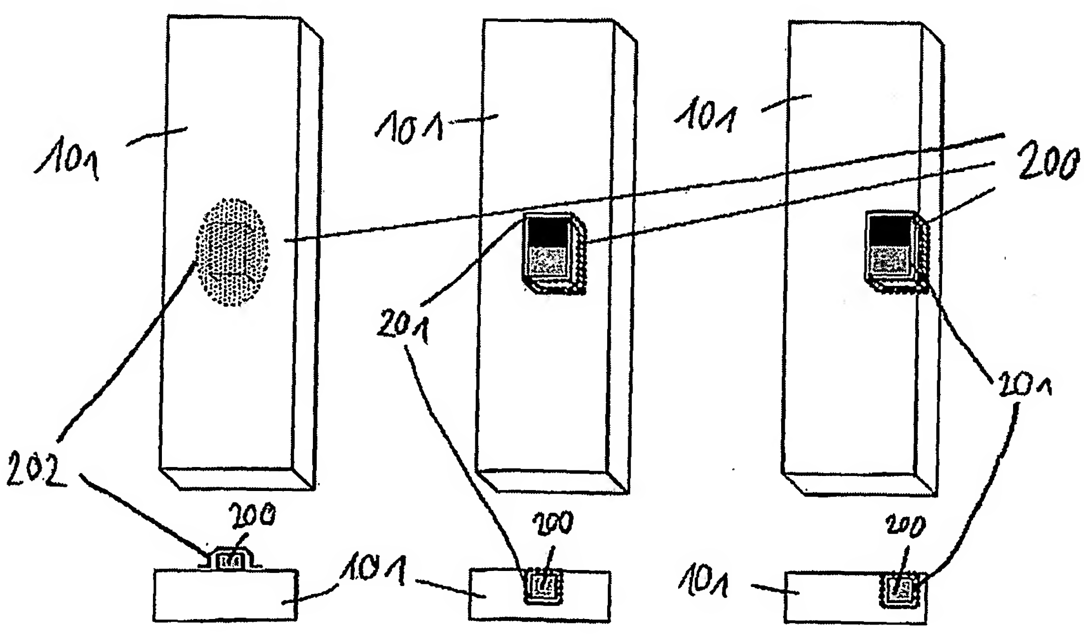
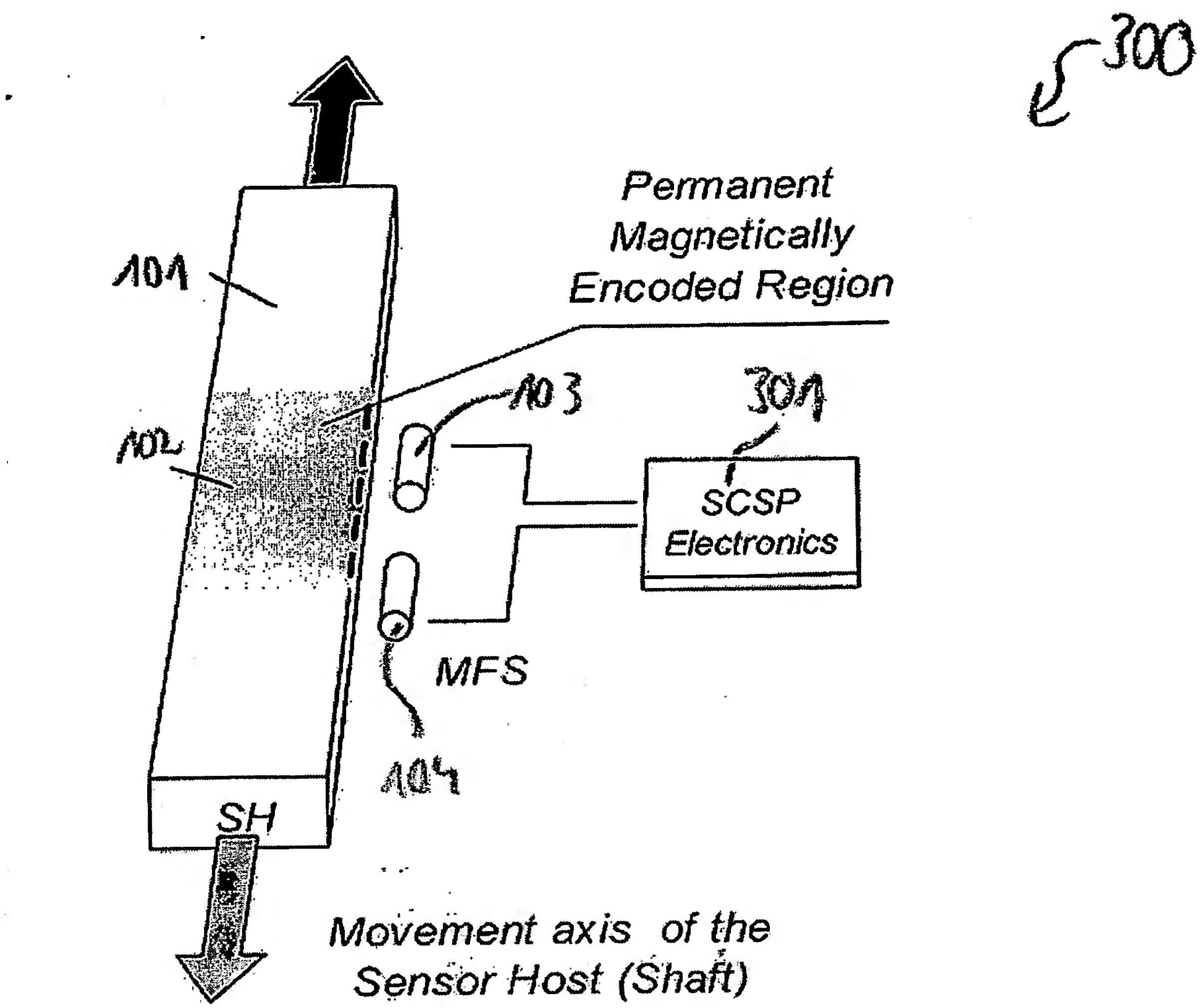
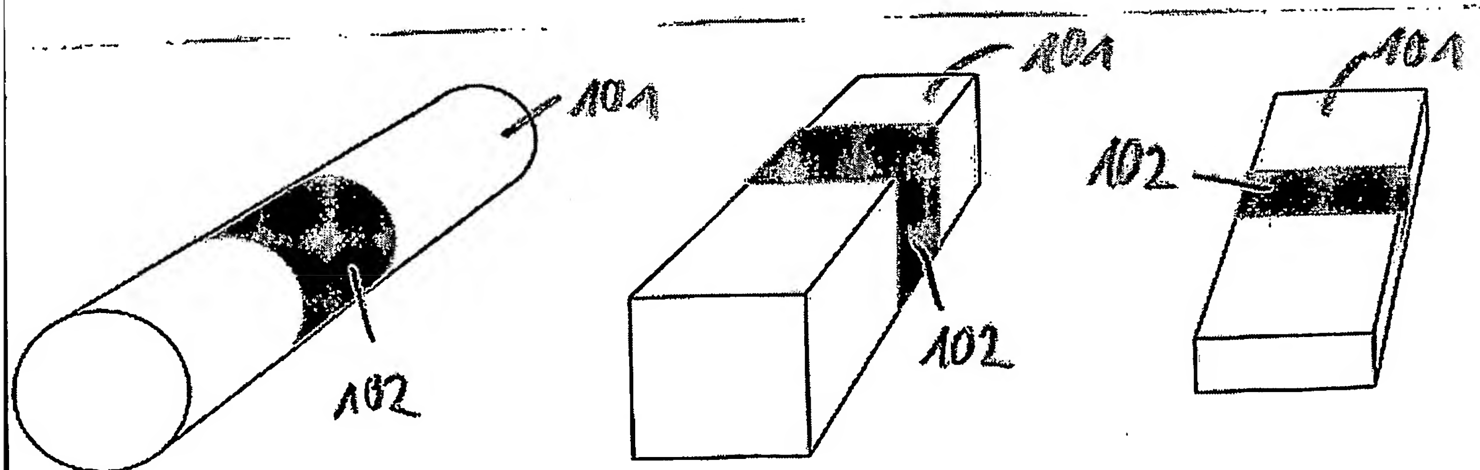


Fig. 2A Fig. 2B Fig. 2C



300
Permanent
Magnetically
Encoded Region
101
102
103
301
SCSP
Electronics
MFS
104
SH
Movement axis of the
Sensor Host (Shaft)

Fig.3A



101
102
101
102
101
102

Fig.3B

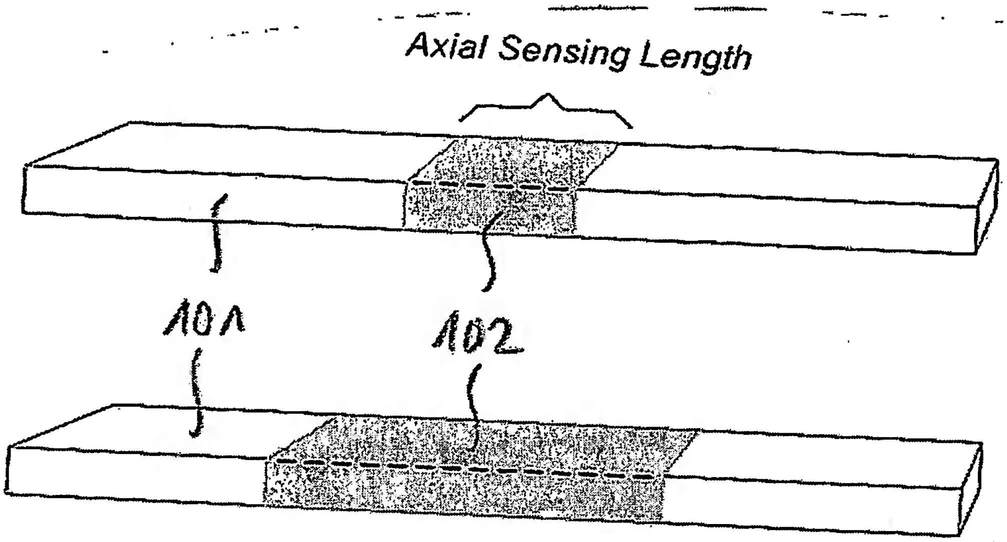


Fig.3C

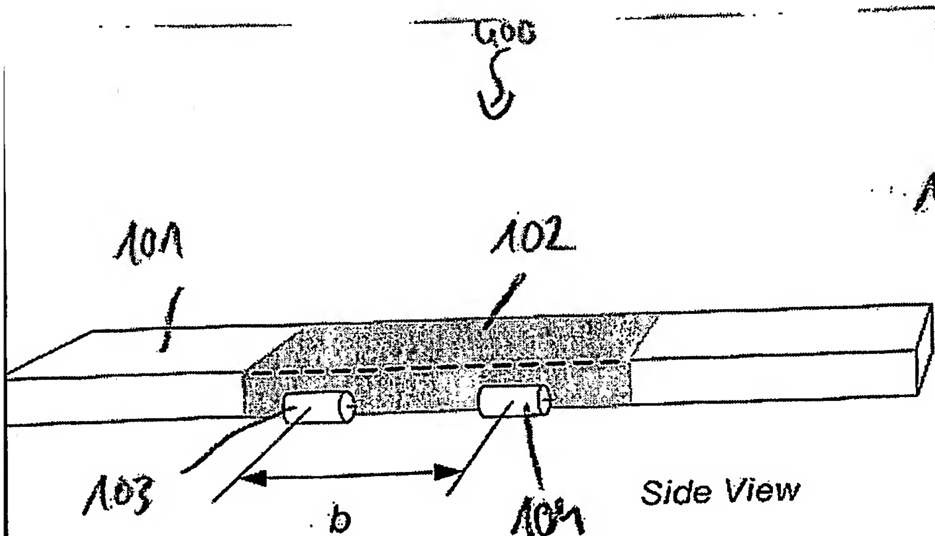


Fig.4A

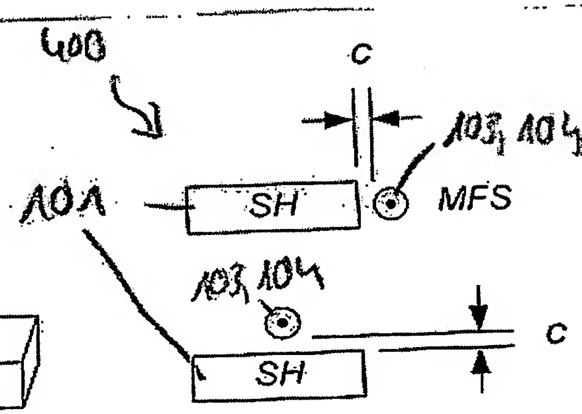
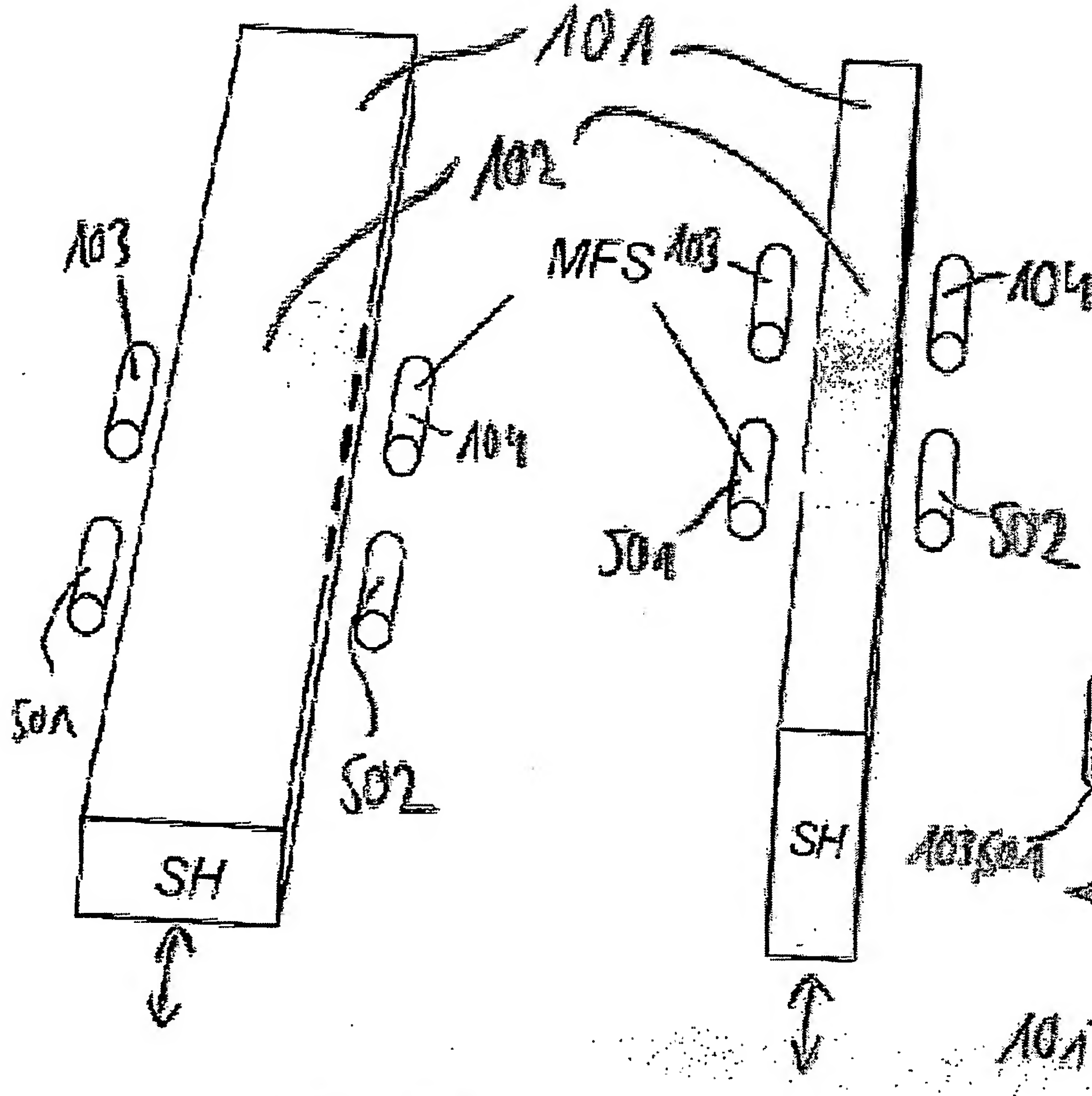
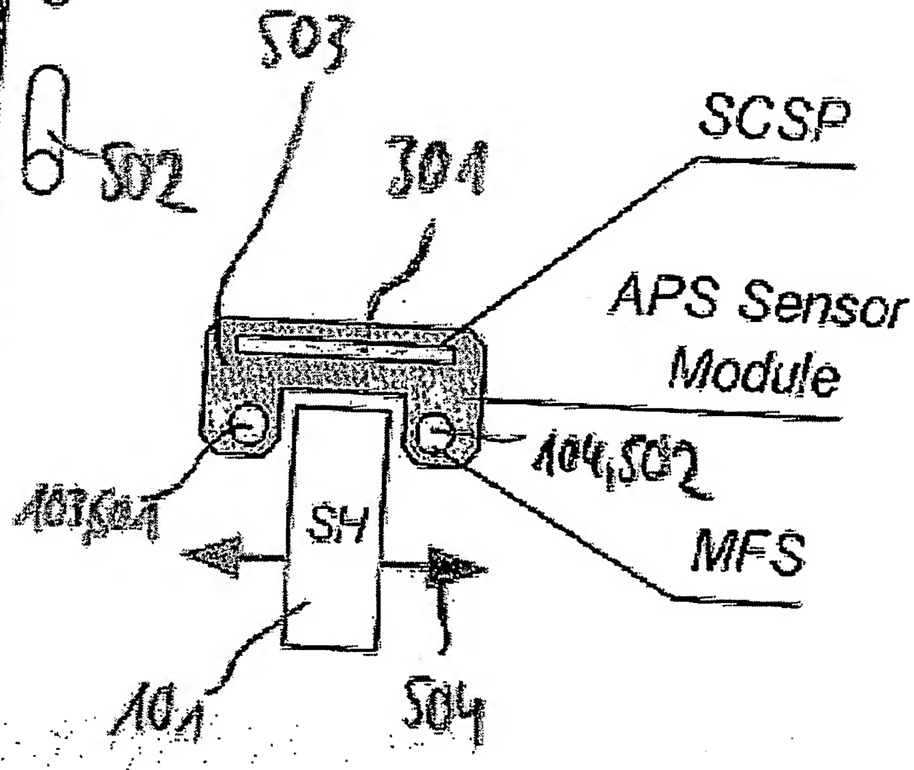


Fig.4B



101
102
103
104
MFS
501
502
503
504
SH

Fig. 5A



503
301
SCSP
APS Sensor
Module
103,501
104,502
MFS
SH
101
504

Fig. 5B

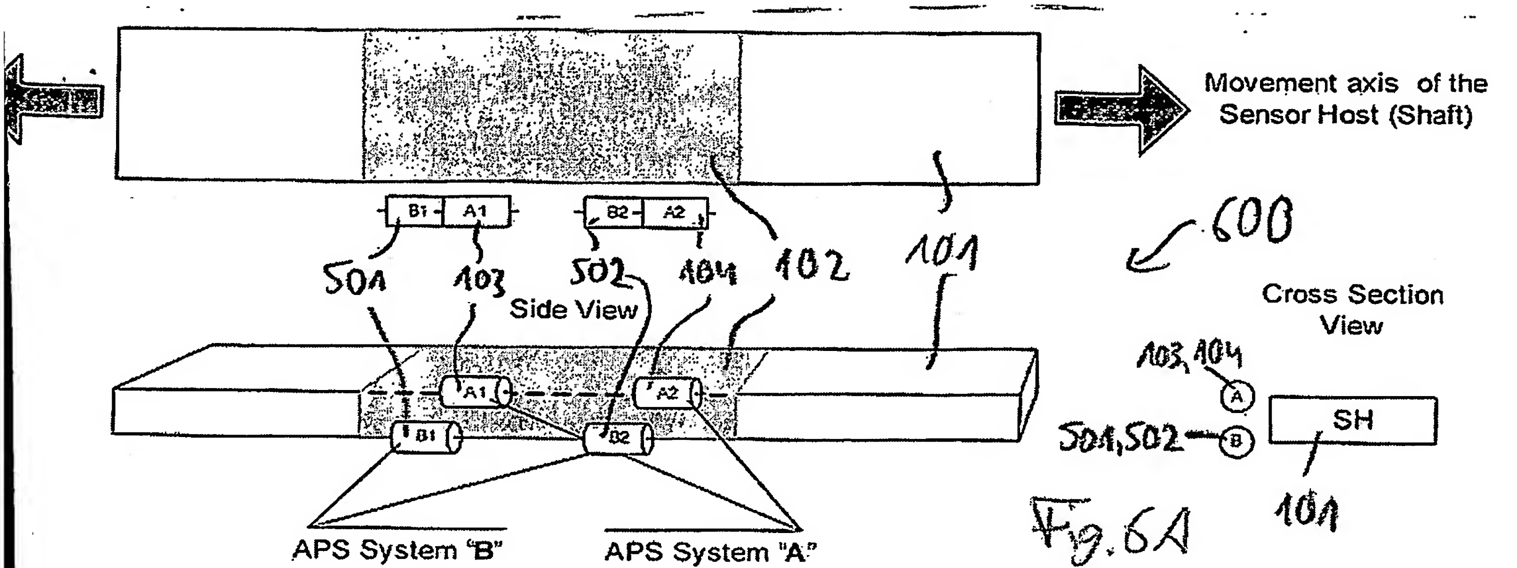


Fig. 6A

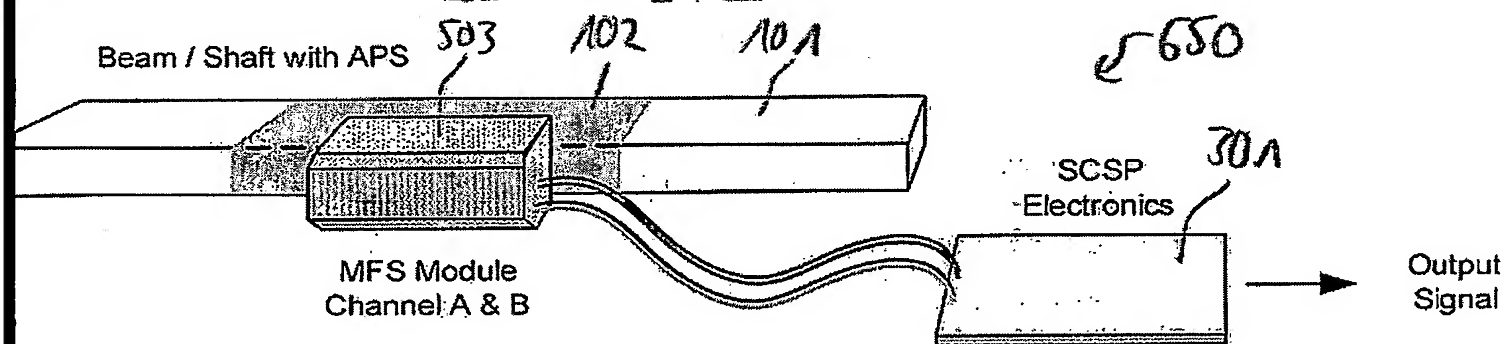


Fig. 6B

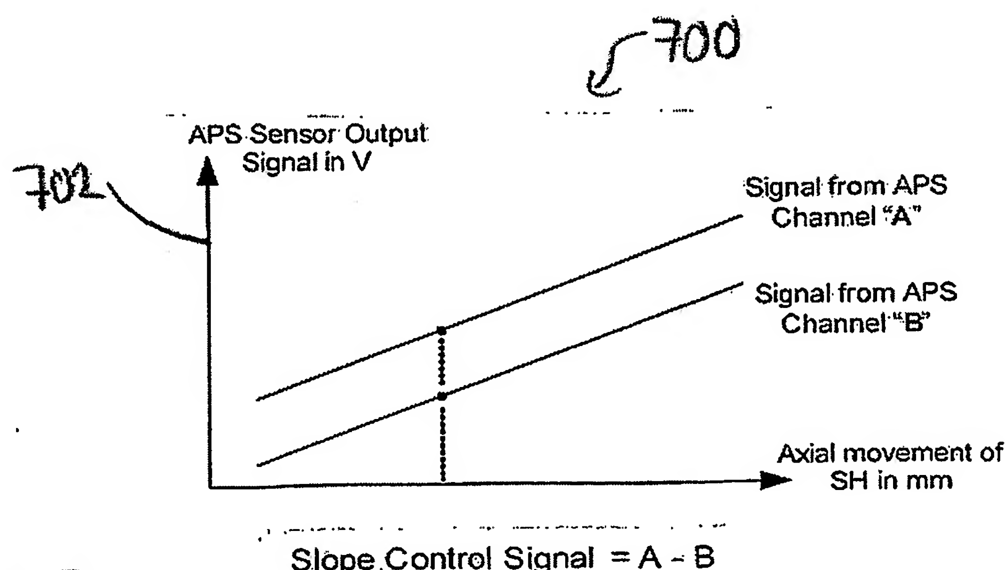
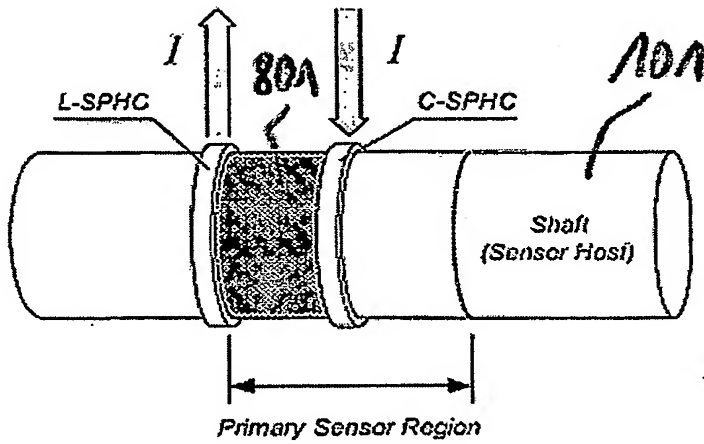


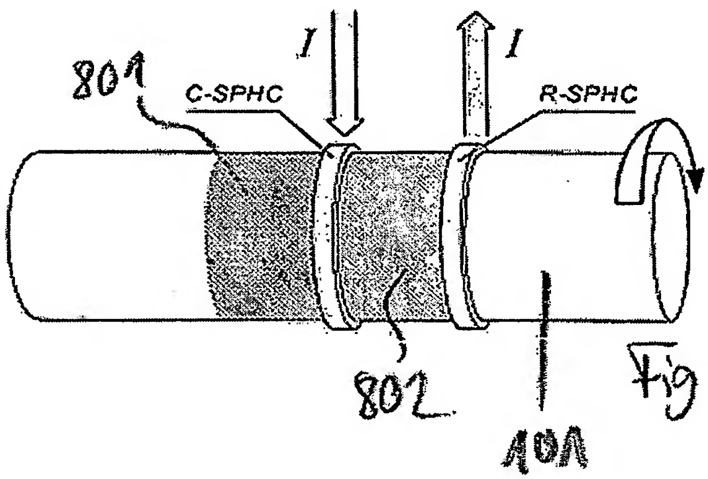
Fig. 7



Encoding Step 1: PCME process applied to SH while no mechanical forces are applied to SH

Fig. 8A

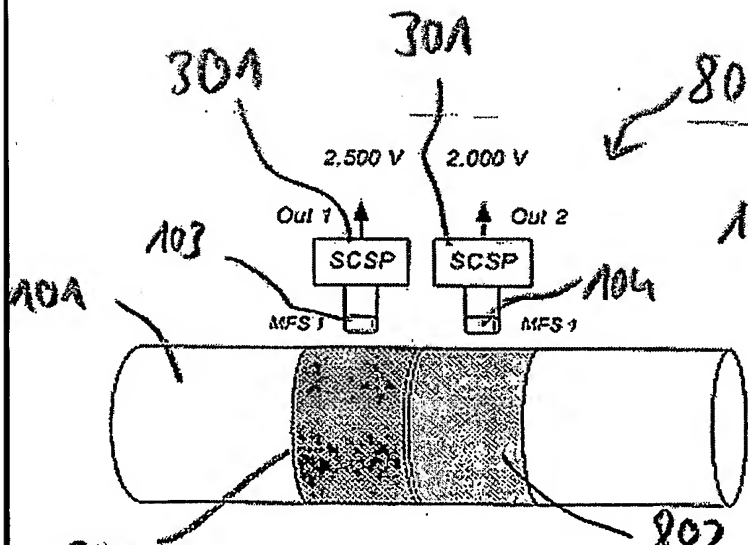
800



Encoding Step 2: PCME process applied to SH while a known mechanical forces is applied to SH

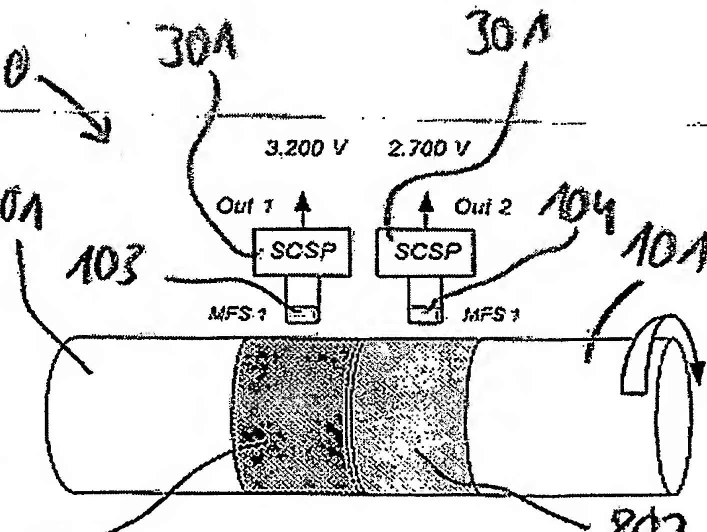
Fig. 8B

800



PCME Sensor with ASC technology when NO mechanical forces applied

Fig. 8C



PCME Sensor with ASC technology when specific torque force applied

Fig. 8D

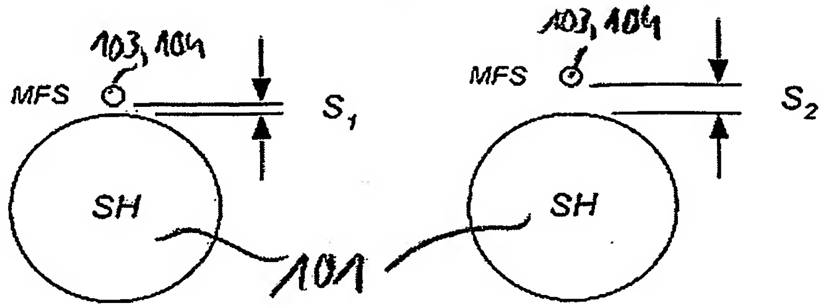


Fig. 9A

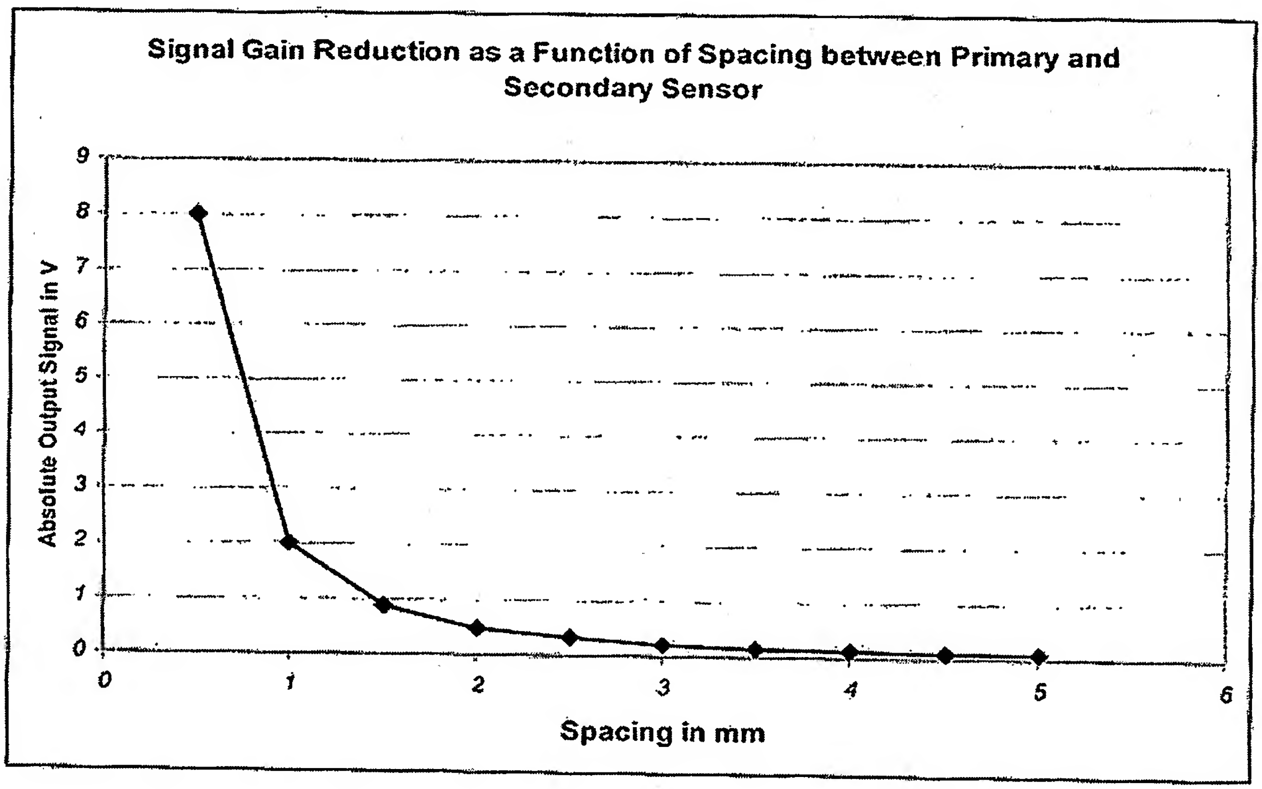


Fig. 9B

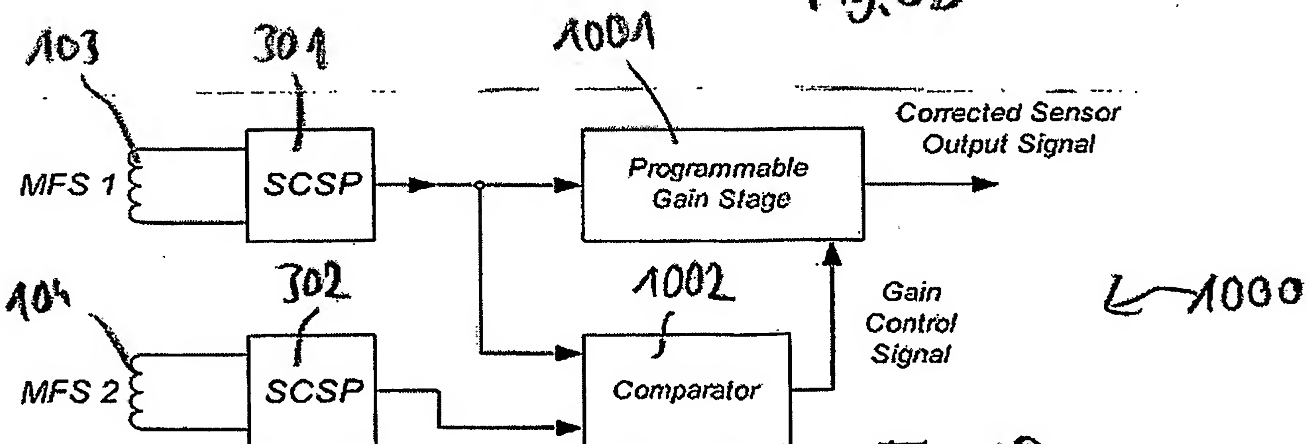


Fig. 10

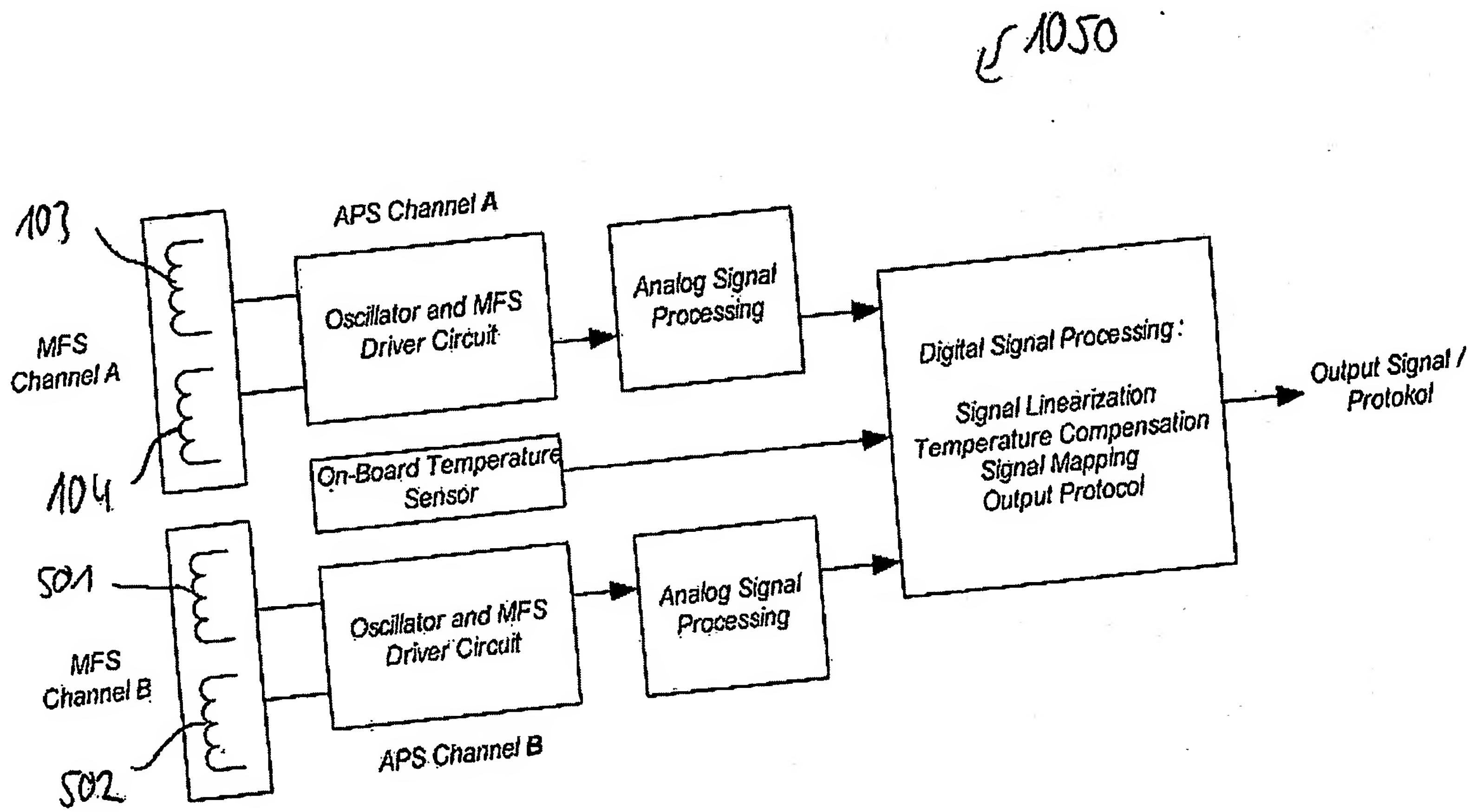

1050
103
104
MFS Channel A
APS Channel A
Oscillator and MFS Driver Circuit
Analog Signal Processing
On-Board Temperature Sensor
501
502
MFS Channel B
APS Channel B
Oscillator and MFS Driver Circuit
Analog Signal Processing
Digital Signal Processing:
Signal Linearization
Temperature Compensation
Signal Mapping
Output Protocol
Output Signal / Protokol

Fig. 10B

Specification	Description	Unit	Value
Max axial measurement range	*Depending on SH cross section*	*mm*	*2 to 45*
Measurement resolution	*In relation to FS (Full Scale)*	*%*	*0.1*
Analog output signal range	*APS output signal, excluding digital processing.*	*V*	*0.2 to 4.8*
Operating temperature range Of the sensing element	*PCME encoding on round SH*	*C^0*	*-50 to + 210*
Operating temperature range of the SCSP electronics		*C^0*	*-50 to +130*
Power supply current consumption	*Single channel, excluding digital*	*mA*	*<10*

Fig. 10C

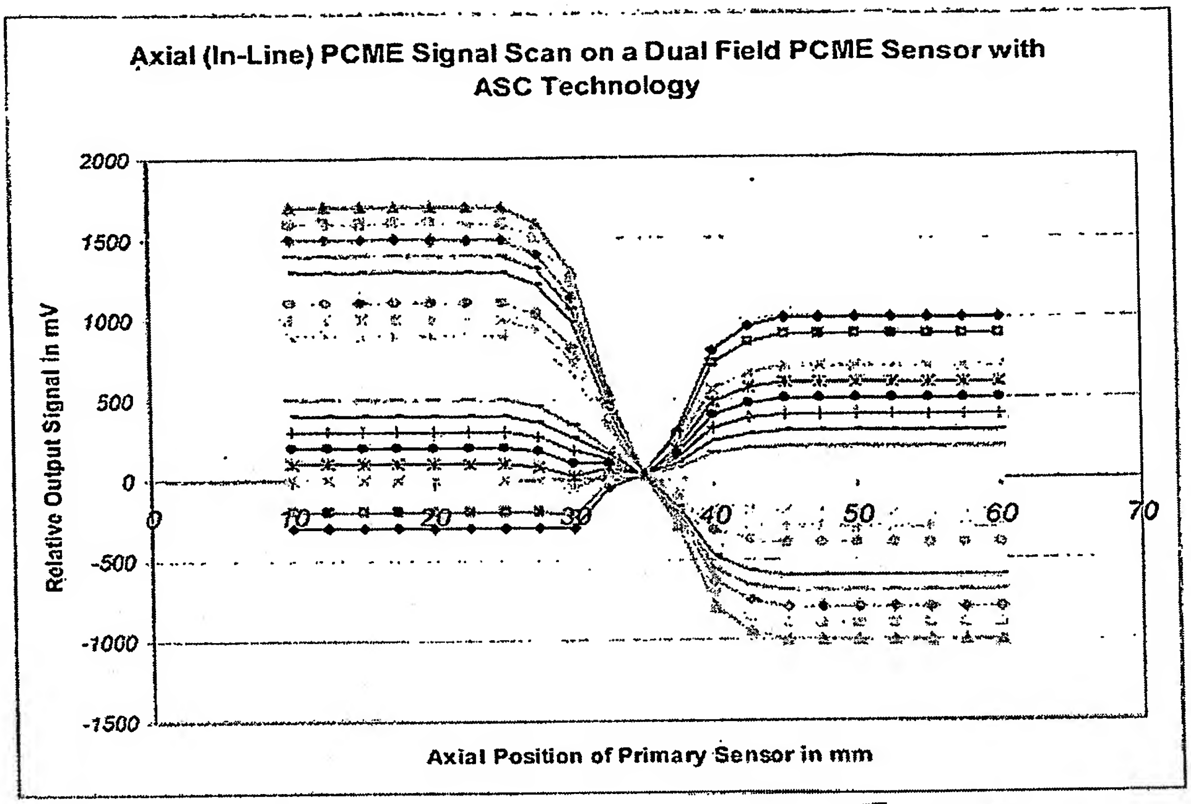


Fig. 11A

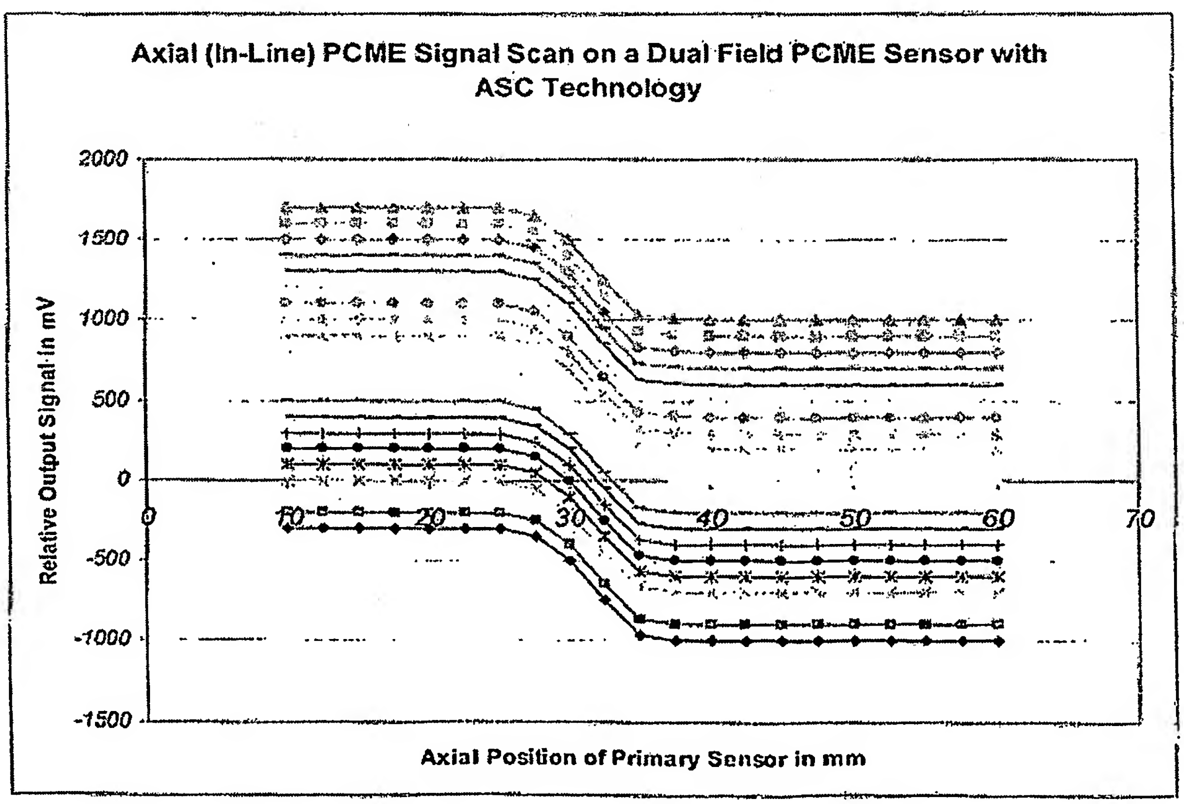


Fig. 11B

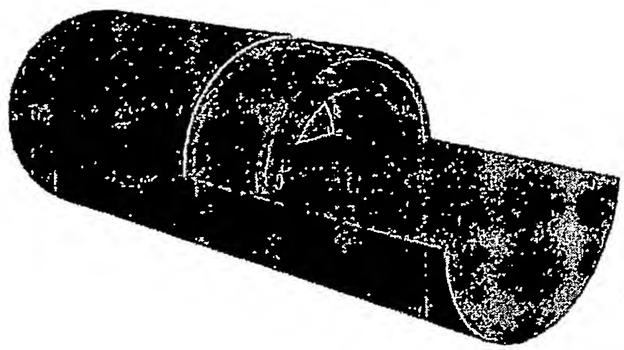


Fig. 12

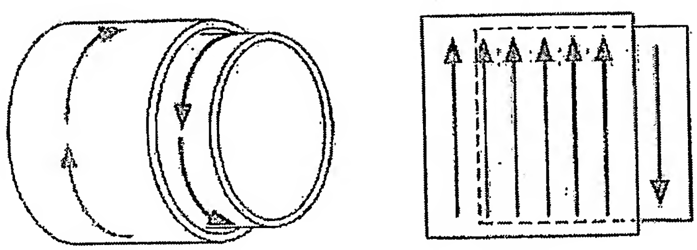


Fig. 13

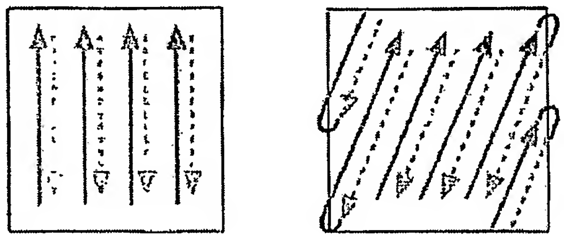


Fig. 14

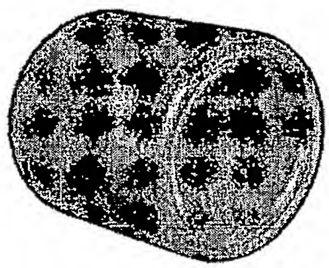


Fig. 15

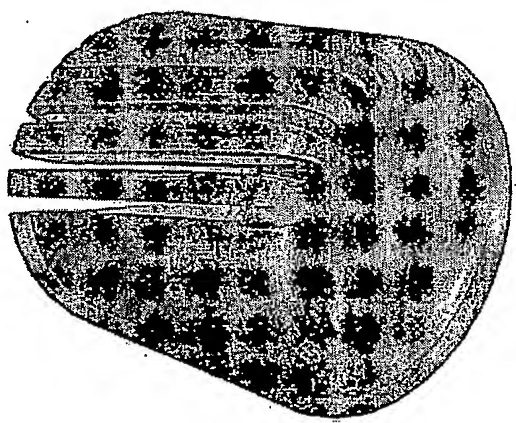


Fig. 16

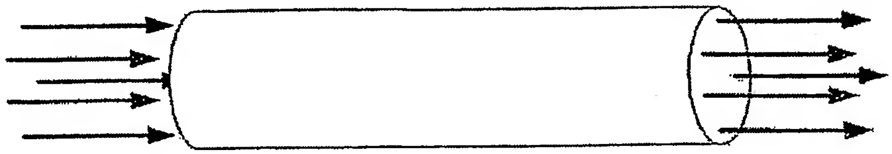


Fig. 17

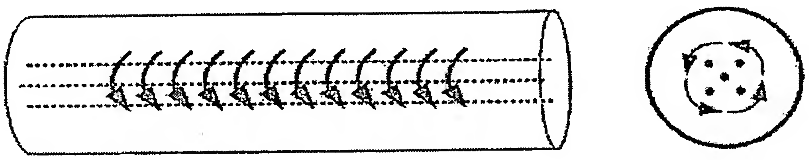


Fig. 18

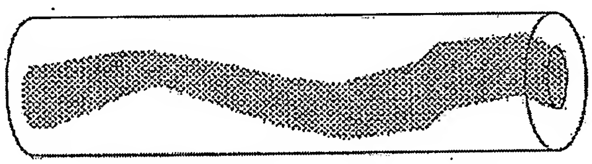


Fig. 19

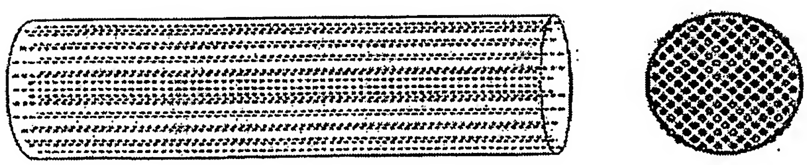


Fig. 20

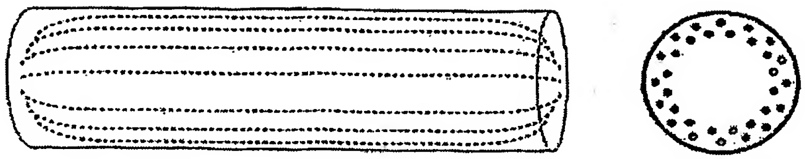


Fig. 21

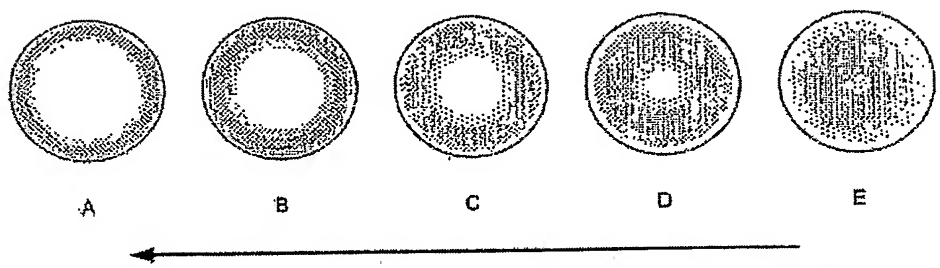


Fig. 22

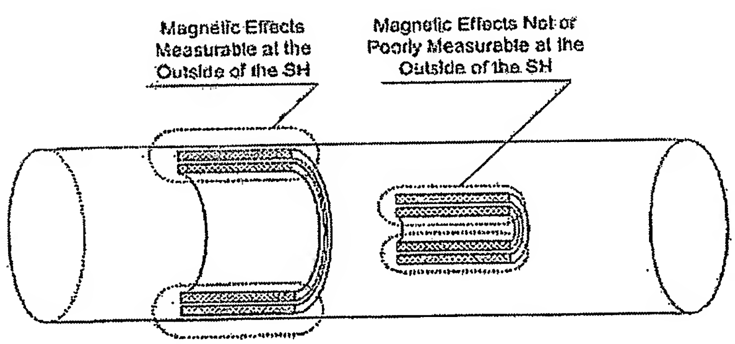


Fig. 23

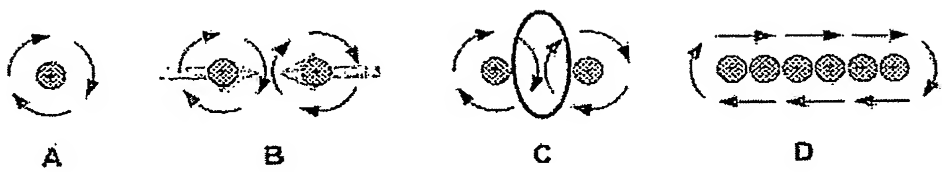


Fig. 24

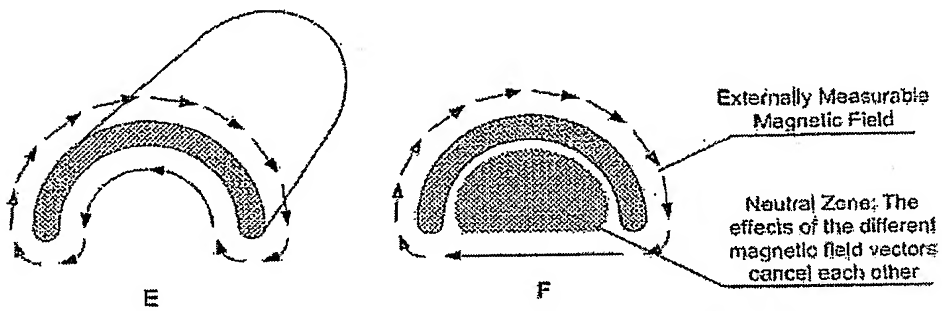


Fig. 25

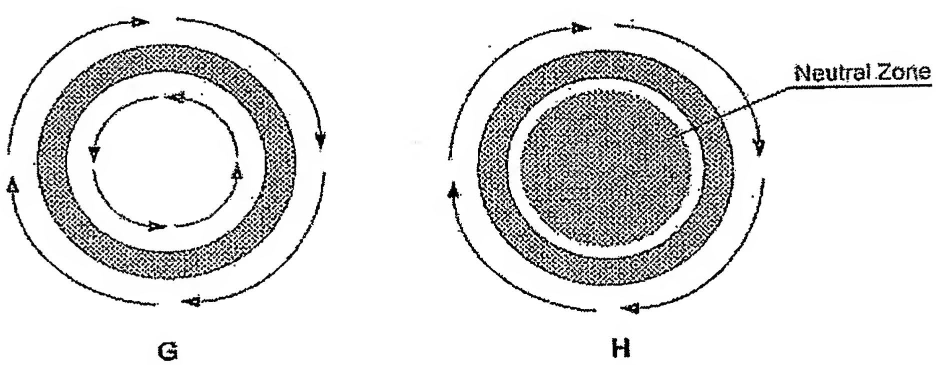


Fig. 26

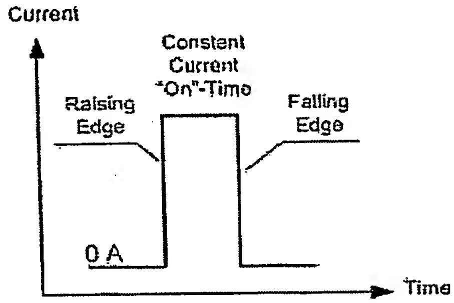

Current
Constant Current "On"-Time
Raising Edge
Falling Edge
0 A
Time

Fig. 27

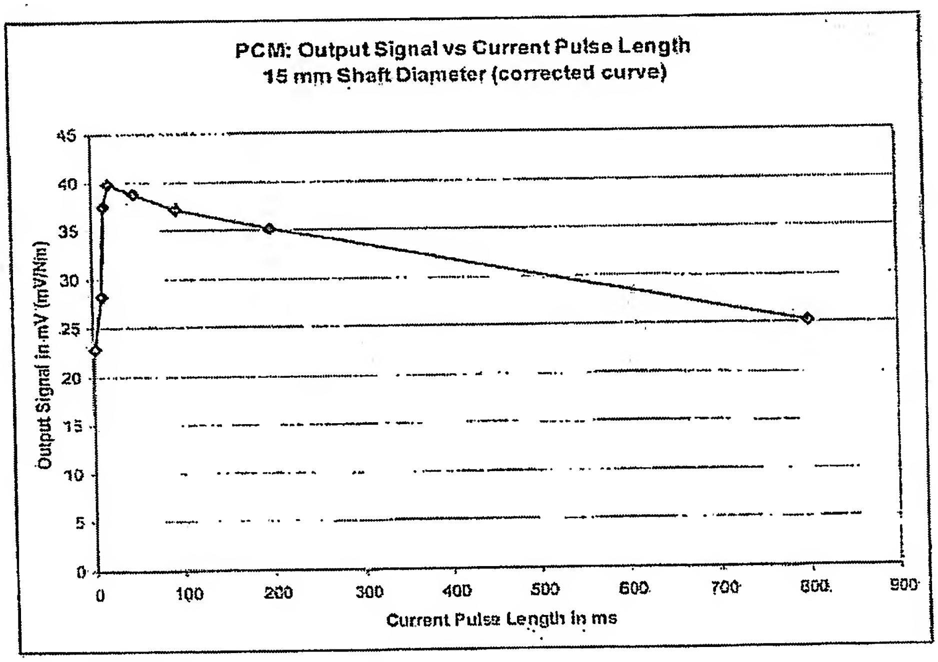

PCM: Output Signal vs Current Pulse Length
15 mm Shaft Diameter (corrected curve)
Output Signal in mV (mV/Nm)
Current Pulse Length in ms
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900

Fig. 28

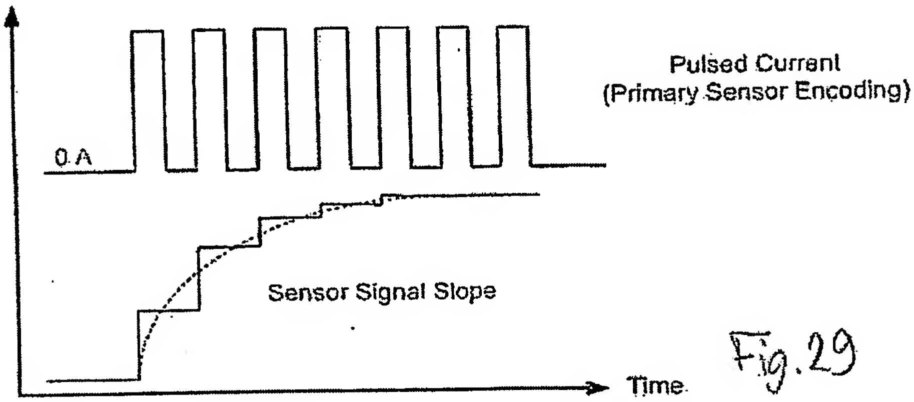


Fig.29

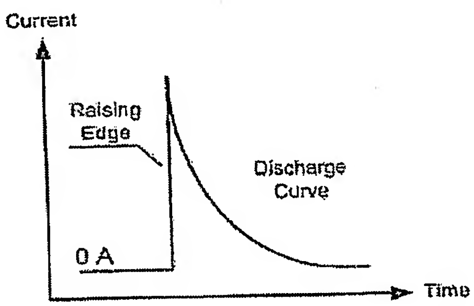


Fig.30

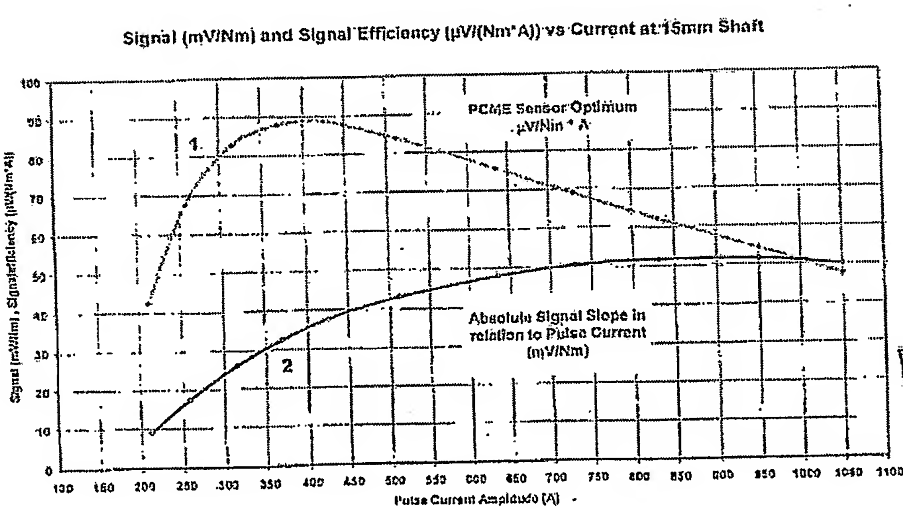


Fig.31

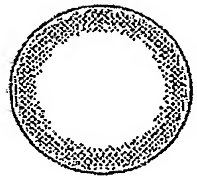


Fig. 32

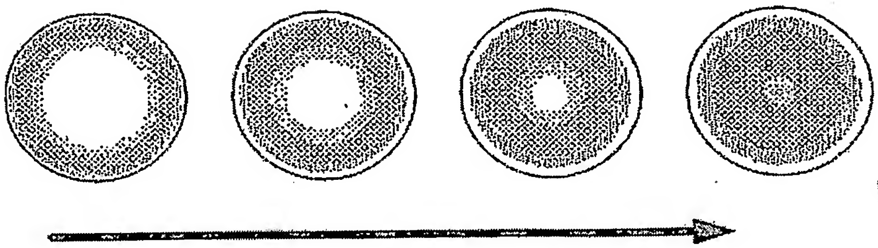


Fig 33

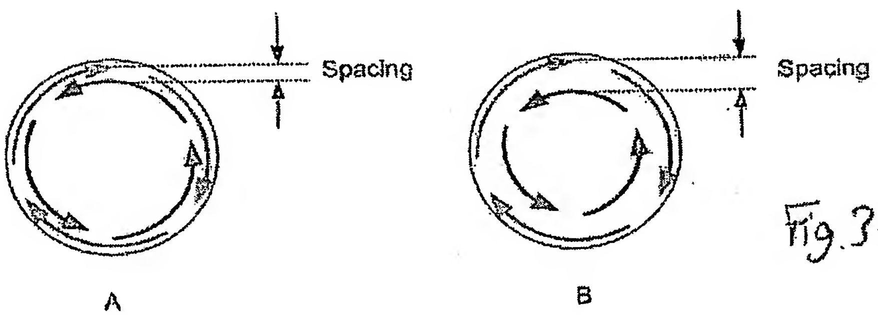


Fig. 34

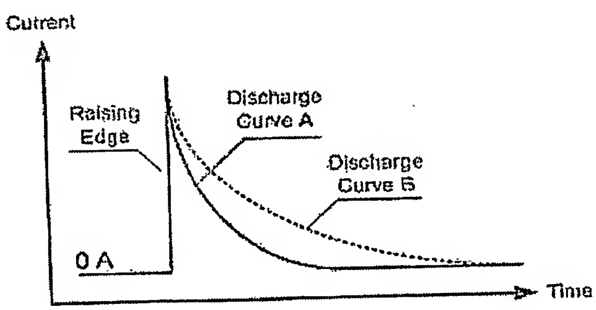


Fig 35

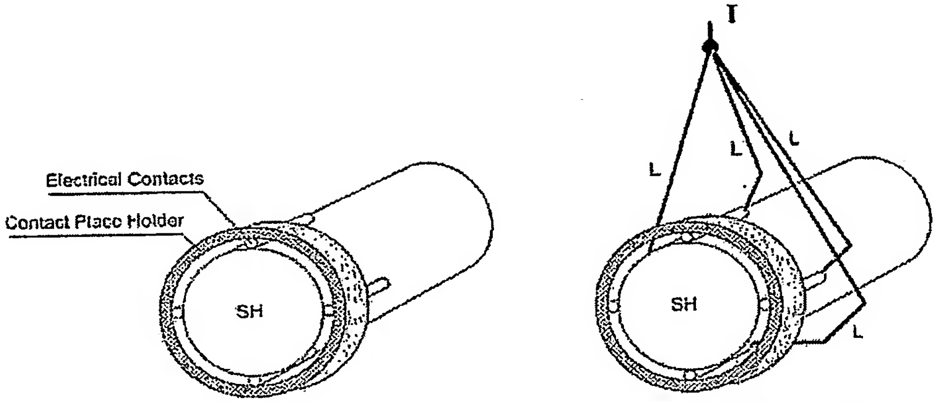


Fig.36

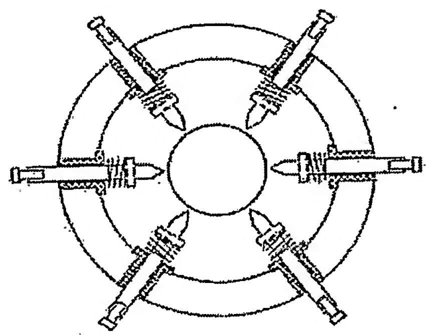


Fig.37

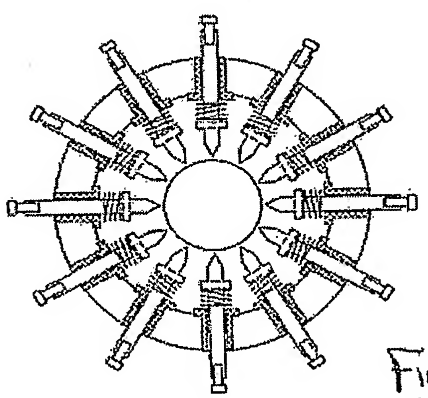


Fig.38

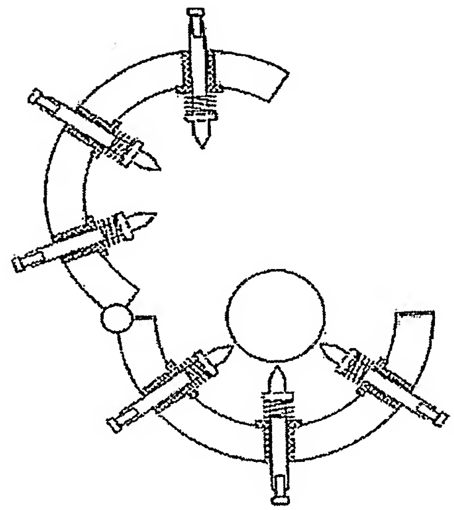


Fig. 39

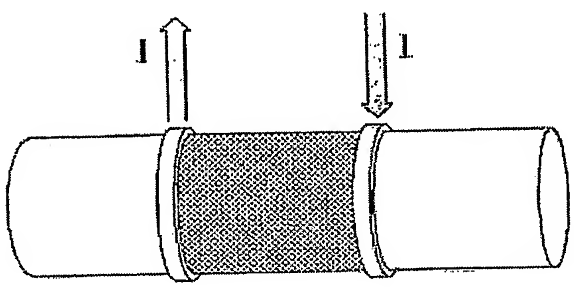


Fig. 40

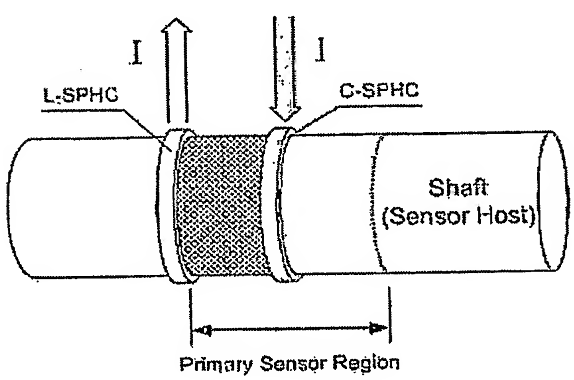


Fig. 41

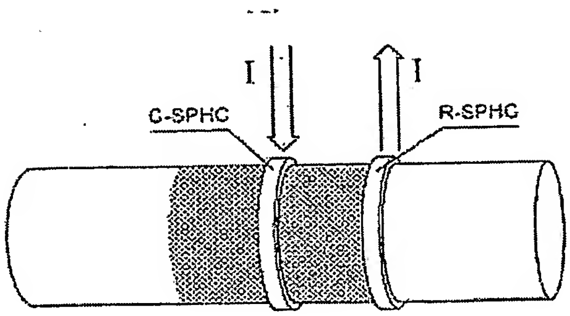


Fig. 42

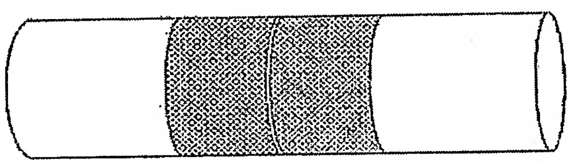


Fig. 43

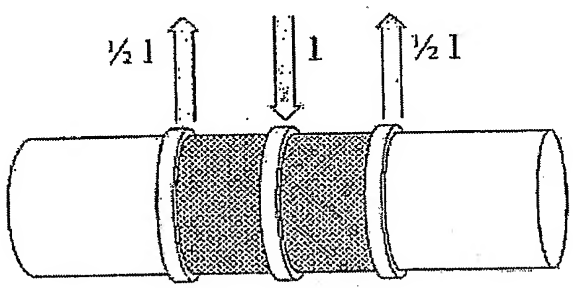


Fig. 44

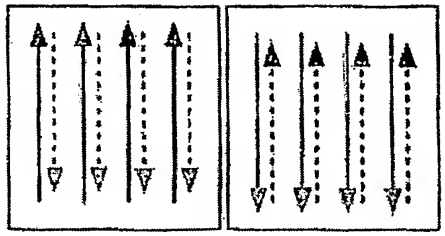


Fig. 45

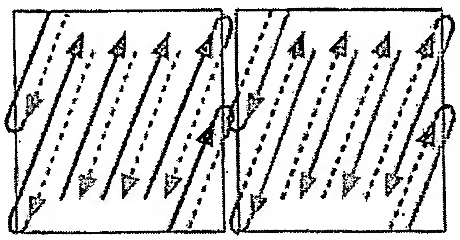


Fig. 46

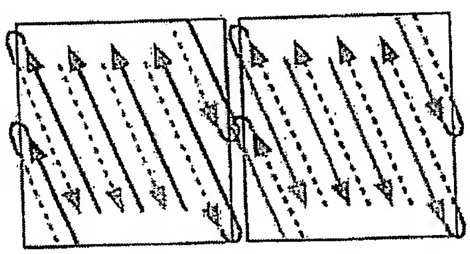


Fig. 47

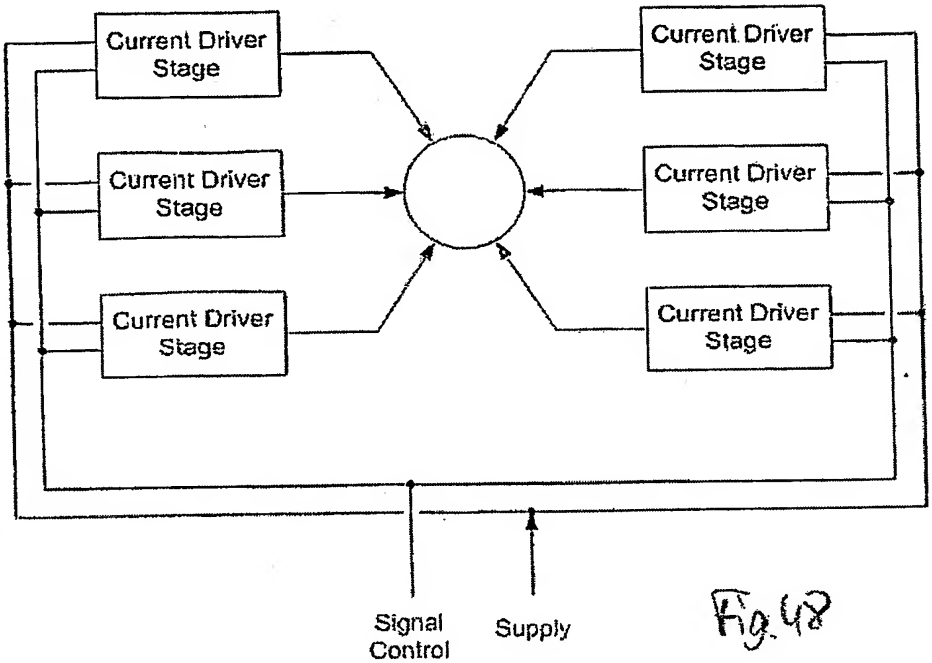

Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Current Driver Stage
Signal Control
Supply

Fig.48

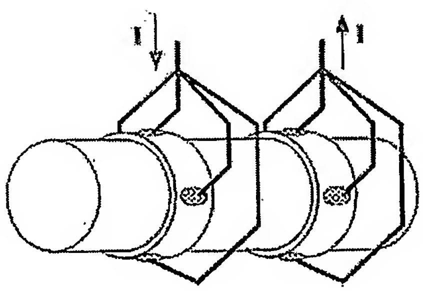

I
I

Fig.49

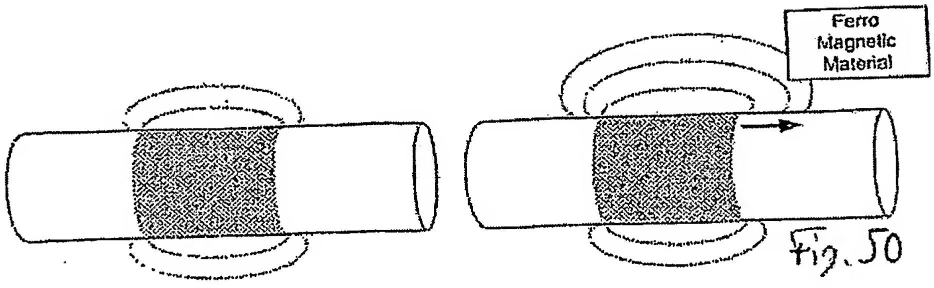


Fig. 50

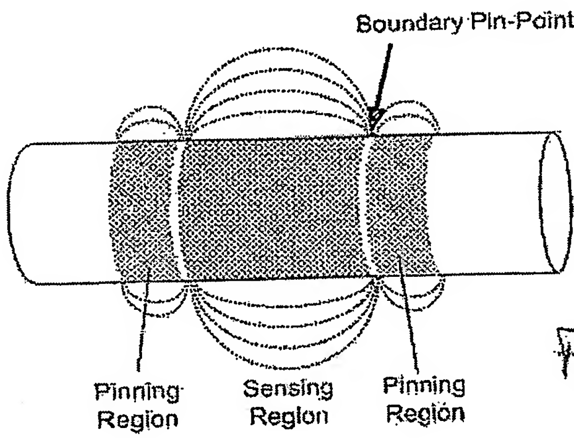


Fig. 51

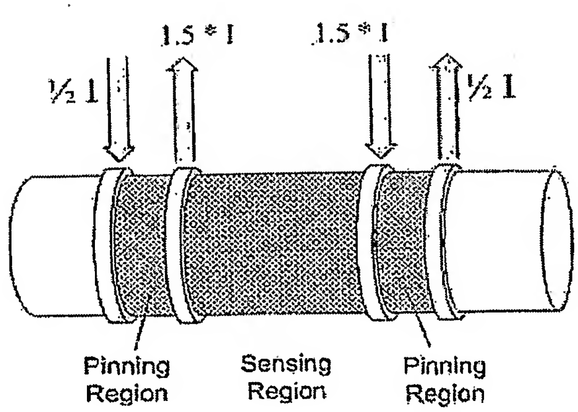


Fig. 52

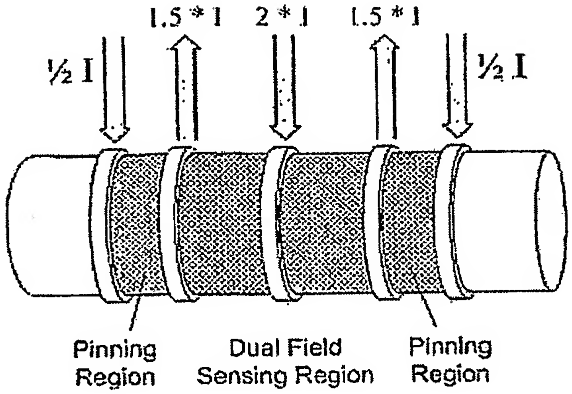


Fig. 53

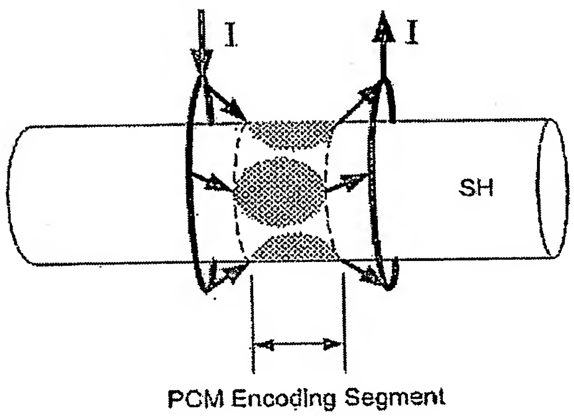


Fig. 54

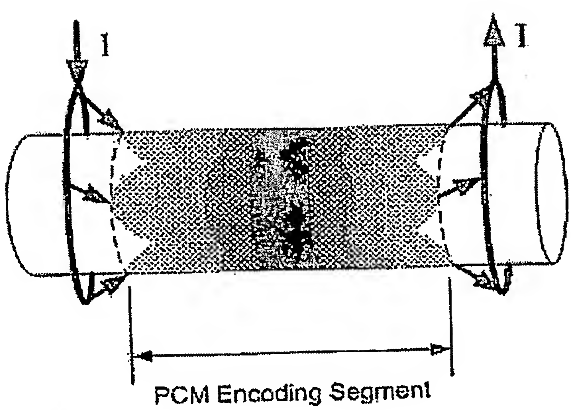


Fig. 55

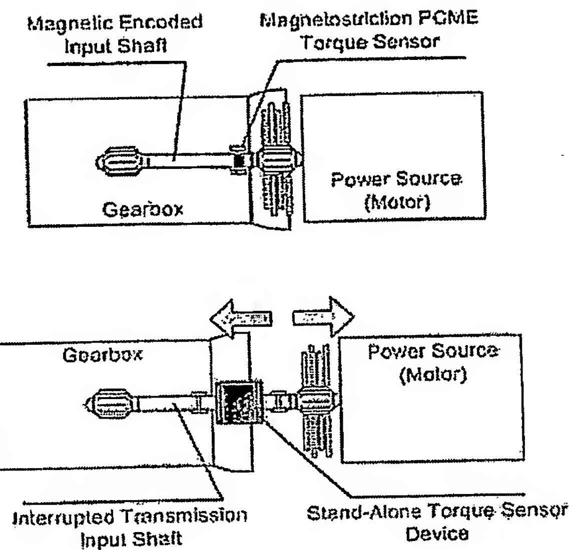

Magnetic Encoded
Input Shaft
Magnetostriction PCME
Torque Sensor
Power Source
(Motor)
Gearbox
Gearbox
Power Source
(Motor)
Interrupted Transmission
Input Shaft
Stand-Alone Torque Sensor
Device

Fig. 56

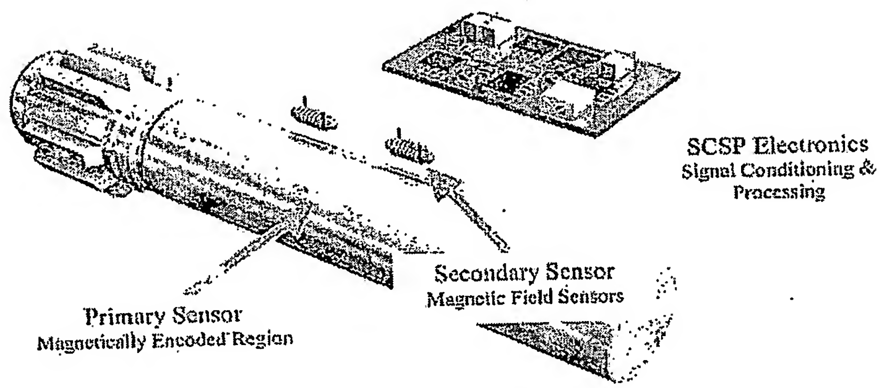

SCSP Electronics
Signal Conditioning &
Processing
Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig. 57

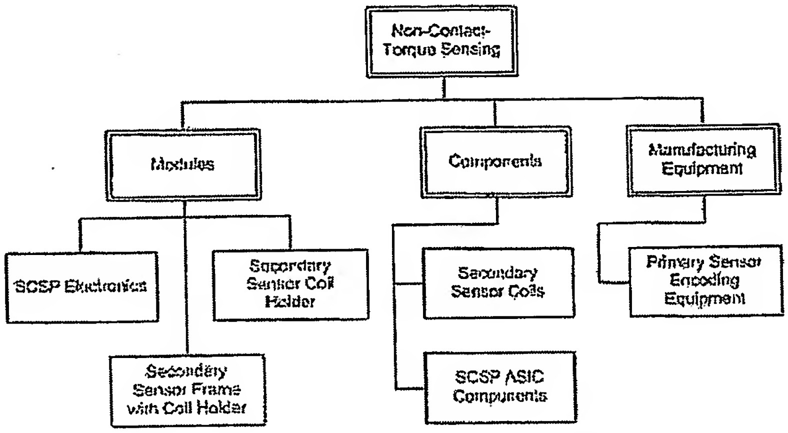


Fig. 58

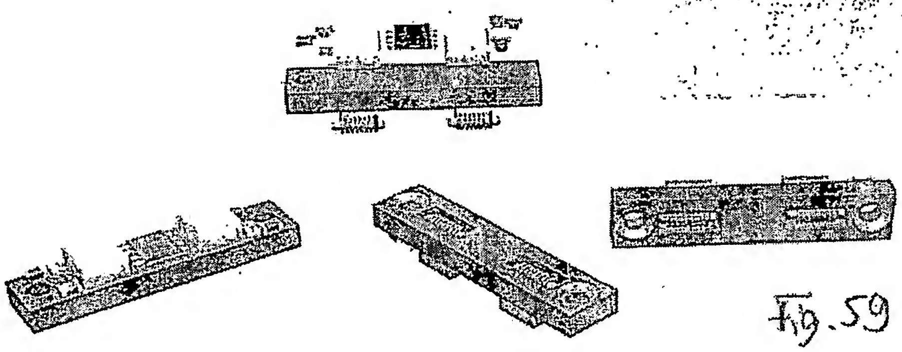


Fig. 59

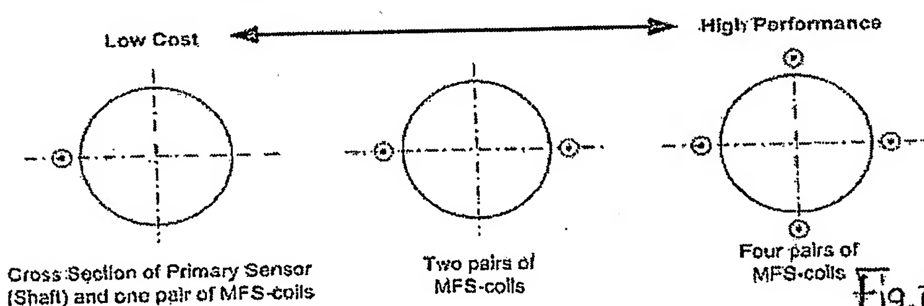


Fig. 60

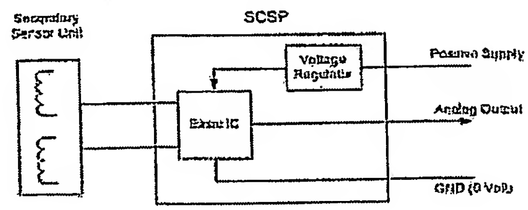

Secondary Sensor Unit
SCSP
Voltage Regulator
Positive Supply
Basic IC
Analog Output
GND (0 Volt)

Fig 61

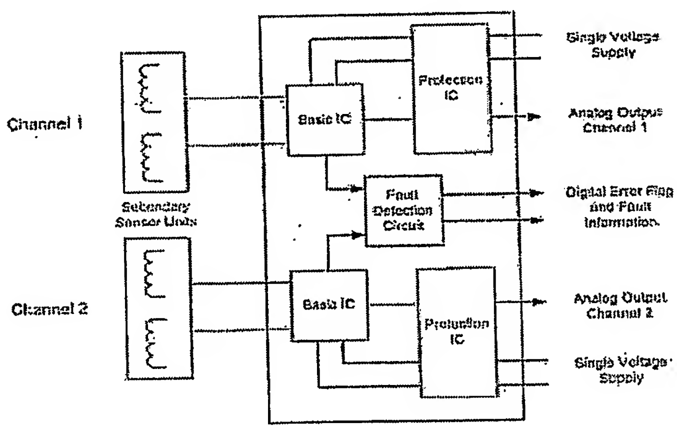

Single Voltage Supply
Protection IC
Channel 1
Basic IC
Analog Output Channel 1
Fault Detection Circuit
Digital Error Flag and Fault Information
Secondary Sensor Units
Channel 2
Basic IC
Protection IC
Analog Output Channel 2
Single Voltage Supply

Fig. 62

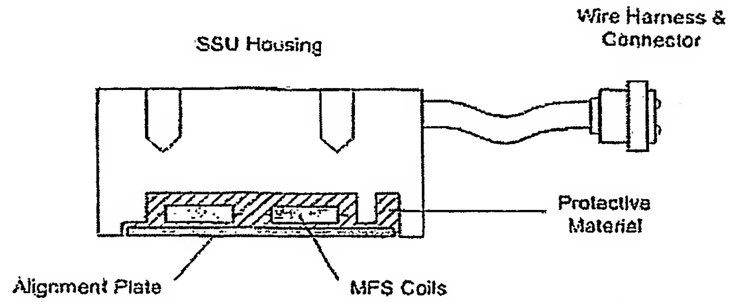

SSU Housing
Wire Harness & Connector
Protective Material
Alignment Plate
MFS Coils

Fig. 63

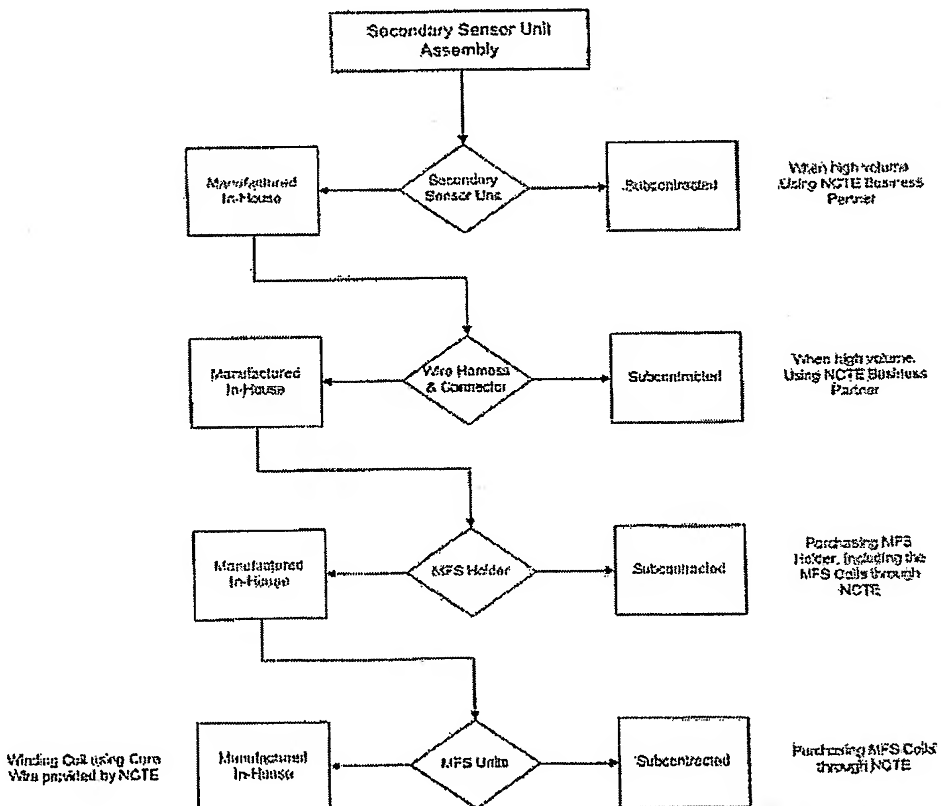

Secondary Sensor Unit Assembly
Manufactured In-House
Secondary Sensor Unit
Subcontracted
When high volume Using NCTE Business Partner
Manufactured In-House
Wire Harness & Connector
Subcontracted
When high volume. Using NCTE Business Partner
Manufactured In-House
MFS Holder
Subcontracted
Purchasing MFS Holder, including the MFS Coils through NCTE
Winding Coil using Core Wire provided by NCTE
Manufactured In-House
MFS Units
Subcontracted
Purchasing MFS Coils through NCTE

Fig. 64

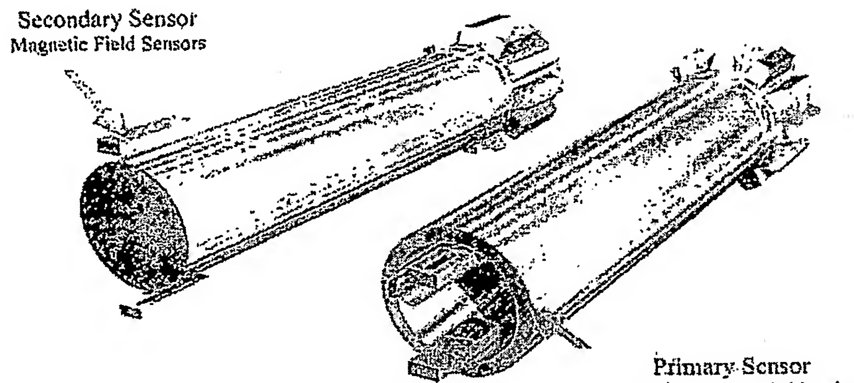

Secondary Sensor
Magnetic Field Sensors
Primary Sensor
Magnetically Encoded Region

Fig. 65

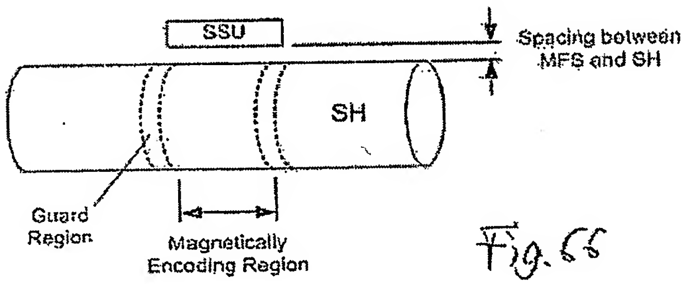

SSU
Spacing between
MFS and SH
SH
Guard
Region
Magnetically
Encoding Region

Fig. 66

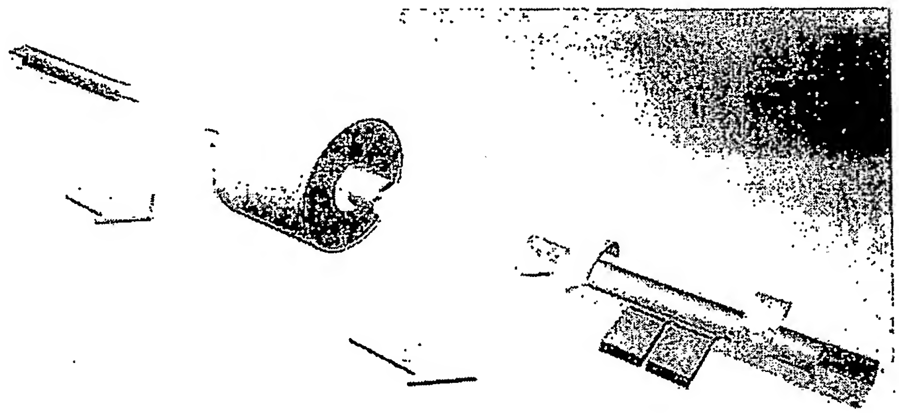


Fig. 67